Inventory Planning and Network Design for Service Parts Logistics

by

Wilson Tandiono

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University of California, Berkeley, 1998

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Signature of Author..
Department of Civil and Environmental Engineering
May 10, 2002

Certified by..
Cynthia Barnhart
Professor of Civil and Environmental Engineering
Thesis Supervisor

Accepted by..
Oral Buyukozturk
Chairman, Departmental Committee on Graduate Studies

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Abstract

We study inventory planning and network design in the context of service parts logistics. Inventory planning involves the stocking of inventory within a company's storage and distribution infrastructure, typically consisting of a central warehouse and field stocking locations (FSL), to satisfy customer demands. Network design involves making infrastructure decisions, such as the location and size of warehouses and FSLs. The objective of this research is to optimize the inventory planning and network design functions. However, the operating environment of service parts logistics presents many challenges, in particular, high demand uncertainty, obsolescence risks, and a very large number of parts. These challenges are exacerbated for third party logistics providers (3PL), that is, companies that specialize in, and perform certain logistics functions for other companies, because they have to handle many customer accounts. Our research is motivated by the study of the operations of a 3PL providing service parts logistics services, and we present models and algorithms that tackle these operational challenges.

The contributions of the thesis are: 1) a perspective and method for facility network design for service parts logistics, 2) in-depth part characteristics analysis, which studies the effect of a part's attributes (e.g., cost, weight, and failure rate) on its optimal inventory stocking plan, and 3) a modular approach to inventory planning, where certain decision-making components are decoupled to gain flexibility and scalability in our models.

Thesis Supervisor: Cynthia Barnhart
Title: Professor of Civil and Environmental Engineering

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Contents

List of Figures

List of Tables

Chapter 1

1.0 Introduction

1.1 Overview

Spare parts are ubiquitous in many commercial and consumer industries, in which products range from computers and automobiles to industrial machines. Spare parts often provide cost economical means of extending the life of an expensive purchase through scheduled maintenance and repairs, which can be in the form of a service contract bundled with the purchase of the product or procured separately from either the seller or another third party. The service contract specifies the terms of the coverage, for example, response time guarantees, price structures, service provider failure penalties, etc. The response time guarantee usually depends on the criticality to the customer's operations of a failed product using the spare part. It can range from very critical medical and industrial equipment where minutes of delay could cost a life or incur expensive downtime, to less critical needs for casual users of equipment (e.g., a second car, leisure fishing boat) in which repairs could wait for days or weeks. In the most time sensitive cases, customers typically stock spare parts in their own facilities; otherwise, they would request response time guarantees of two hours, four hours, or next day, and so forth.

We refer readers to Cohen's extensive coverage of the service parts industry in terms of current industrial practices and trends in service logistics operations for computer products (Cohen et. al. [4]). Companies providing after-sales service typically use multi-echelon distribution networks (see Figure 1), consisting of different tiers of distribution centers (DC) and local field stocking locations (FSL), to deliver parts to a geographically dispersed customer base.

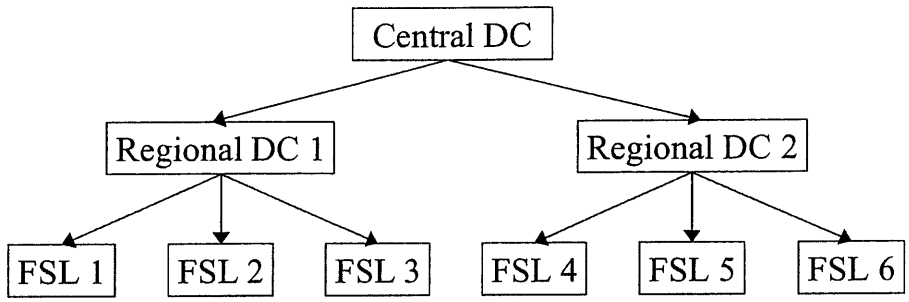

Figure 1. Multi-Echelon Distribution Network.

The echelon structure allows for quick responses in delivery from the local echelons to the customers, and designated replenishments (as represented by arrows in Figure 1) from the upper to lower stocking echelons. The FSLs tend to be smaller than the DCs because they serve a smaller range of demands, and are usually located near cities where building a large warehouse is cost prohibitive. Muckstadt and Thomas ([25]) show that multi-echelon systems inherently perform better than single location models for spare parts. In Cohen's survey ([4]), the majority of companies can achieve high fill-rates within 24 hours, but only a few offer quicker responses of 2 hours. Trucking is the predominant mode of replenishment to the lower echelons. However, companies have recently tapped into the competitive air shipment market for regular or quicker emergency replenishments between the stocking locations, and regular customer deliveries, because of the shorter lead times and wider coverage range, which allows for greater centralization of inventory and substantial inventory savings.

Customers tend to be demanding and sensitive to the ability of the service providers to satisfy their response time obligations, and most companies cannot afford the potential loss of goodwill from recurring bad service; hence, fulfilling service levels is the crux of the service parts business. The goal then is to stock the right parts at the right places, and deliver the parts at the right time to the customers in a cost effective and resource efficient manner. This is the purpose of Service Parts Planning (SPP), which involves the efficient management of procurement, storage, distribution, and delivery of spare parts, with the purpose of satisfying customers' contractual service obligations effectively.

Both Wang ([33]), and Alfredsson and Verridjt ([1]) provided comprehensive reviews of the SPP literature, and the former delved into detailed discussions of a few previously studied models. Most notably, early SPP literature has focused on determining optimal stocking levels for multi-echelon systems with stochastic demand, starting from Sherbrooke's approximate METRIC model ([29]). Simon ([32]), Kruse ([20]), and Shanker ([27]) extended the METRIC model by offering an exact solution approach. Muckstadt and Thomas ([25]) incorporated into METRIC emergency supplier replenishments, which are faster replenishments between the supplier and DC, and from DC to FSL. Graves ([17]) used a different modeling approach from the METRIC model for the distribution of net inventory level to achieve improved results. Axsater ([2]) compared his model with Lee's ([22]), with both models incorporating lateral transshipments (the process of either fulfilling a customer order from another FSL not previously assigned to the customer, or replenishing stock within the same echelon level instead of the regular upper to lower echelon replenishments). Dada ([13]) studied emergency supplier replenishments and lateral transshipments using Markov analysis. Approximate methods were deployed because model size grows exponentially with problem size, and exact analysis is quickly rendered computationally intractable.

Alfredsson and Verridjt ([1]) reinforced the importance of these emergency shipments in SPP through their less restrictive model, which had the same modeling approach as Dada's ([13]). Graves ([18]) also formulated a new modeling approach using virtual allocation of upper echelon inventory (i.e., stock at an upper echelon is reserved as demand occurs at a lower echelon) and fixed replenishment schedules. A series of publications by Cohen, Kleindorfer, and Lee ([8], [9], [10], and [11]) led to the development of Optimizer ([7]), a multi-echelon service parts system implemented for IBM's spare parts logistics operations. The Optimizer employed a combination of heuristics, decomposition techniques, and regression.

The SPP literature mentioned so far has treated the locations of DCs and FSLs in the distribution network as fixed. Shen ([28]), however, took a joint inventory and location approach to modeling the distribution of blood platelets in blood bank operations. His work capitalized on the seminal work by Eppen ([16]), which quantified the inventory savings from risk pooling. Risk pooling is essentially the reduction of variability by aggregating demand together, because individual demand patterns tend to negate each other; hence, less safety stock is required to guard against uncertainties in demand. We further elaborate the concept of risk pooling in chapter 3. The reader is referred to Daskin ([14]) for an excellent coverage of facility location models.

1.2 Industry Characteristics and Challenges

Towards the end of the 21st century, businesses in the U.S. have ventured beyond traditional requirements of low cost and high product quality, and started to devote increasing attention to customer satisfaction, as a means of retaining existing customers and attracting new ones. Because the deal is not entirely done at the time of sale, companies can further increase customer satisfaction using excellent post-sales support, and foster customer intimacy through personalized and attentive service. Thus, post-sale services can be leveraged as competitive advantages and help establish brand loyalty ([15]). Some companies, like Dell and Saturn ([5]), have successfully positioned their excellent customer support services as value-added services, to create niche markets for customers who demand not only a good product, but also comprehensive and responsive customer service (e.g., 24hr response guarantees, quick turnaround times, flexible service hours, etc.). Customers often include the quality and past experiences of post-sales service as a determining factor in making future purchasing decisions. Its positive impact on boosting sales from returning and new customers is reflected by the fact that service parts management has provided a significant revenue stream for many companies. According to an industry survey, service parts revenues constitutes up to 30% of sales ([4]) and accounts for up to 30-40% of profits in some cases. Running a robust SPP system, however, is not easy due to the following industry characteristics:

1) Obsolescence

Managing obsolescence cost is perhaps the biggest challenge in SPP. Most parts eventually become obsolete, which often creates a dilemma, in which companies have to decide whether to discontinue stocking these parts at the expense of not providing support for the remaining installations. Such SKUs are expensive to maintain as they tie up capital, warehouse space, and planning resources. Moreover, they usually end up scrapped, returned to the manufacturer, or sold at deep discounts to the remaining customers. Short product lifecycles have exacerbated the obsolescence predicament as more SKUs become obsolete quicker, as reflected by the fact that obsolescence, scrap, and shrinkage account for, on average, almost a fifth of operating costs ([4]).

2) Cost-service tradeoff

As in many industries, the tradeoff between cost and service level is also intrinsic to SPP. More inventory stock and greater infrastructure investment generates higher levels of service. On the other hand, service failures are risked by stocking too little inventory and stretching resources too thinly. The goal is to balance inventory investment and service levels provided, in alignment with the company's strategy. Companies need to understand these tradeoffs well, so that they can determine an efficient frontier of the cost-service tradeoff curve, and exercise better judgment on where to position themselves on it.

3) "Just-in-case" mentality

Hoarding spare parts is the manifestation of the "just-in-case" mentality. While it is necessary to build up safety stocks to account for unexpected failures, many companies have excessively inflated safety stocks. With effective SPP, inventory can be minimized and customer service obligations met simultaneously. A challenge, however, is to convince planners to maintain an appropriate stocking policy, and not be misguided by the need to satisfy a sense of security with excessive safety stock.

4) High demand and supply uncertainty

The demand for spare parts is usually triggered by equipment failure, which is highly unpredictable. Although some manufacturers specify expected Mean Time Between Failures (MTBF), they provide only rough guidelines and are subject to differing operational uses and treatment. The exponential behavior of equipment failures means that the equipment could fail anytime with a certain probability depending on its failure rate; hence, resulting in high demand variability. Accurate forecasts are difficult to obtain, if not, impossible. Safety stocks are the instinctive answer to demand uncertainty, and the greater the demand variability, the more safety stock required to achieve the same level of service. Unlike some production or assembly operations where demand is steady enough to implement Just-In-Time (JIT) systems to minimize inventory, the sporadic nature of demand for spare parts makes significant inventory outlays intrinsic in service parts operations. Therefore, inventory assets could represent as much as 50% of typical service parts operations costs ([21]).

5) Stock Keeping Unit (SKU) proliferation

The number of SKUs has increased exponentially because of greater product complexity and broader offerings. This situation is especially evident in the high tech industry (e.g., electronics, computers, etc.) where innovation-based competition has triggered frequent new product offerings and driven product lifecycles down to an average of 18 months. In an industry survey, companies on average, stock close to 100,000 parts each ([4]). The SKU count can easily run into the millions for third party logistics providers (3PL), that is, companies that specialize in and perform certain logistics functions (e.g., transportation, warehousing, inventory management) for other companies. The vast number of SKUs greatly increases the operational and planning complexity in SPP, because every SKU must be tracked and planned. In addition, the numerous parts and their design complexities complicates technician training, even within their respective specialized fields.

To alleviate the problem of SKU proliferation, many companies have taken integrative approaches in their design process. This has resulted in modularization, which is the design of products with standard part interfaces that allows a component or group of components to be easily removed and replaced, whether for faulty or upgrade reasons. Modularization allows for quick repairs by field technicians, as they can better trace the malfunction to a specific module, and need only replace it with a working one. Products are also designed with part commonality considerations to reduce the number of SKUs, and to allow part sharing across products. By sharing more components and aggregating common part demand across product lines, demand variance is reduced, which makes inventory planning and high service levels more manageable and achievable. Despite efforts of modularization and common parts, nevertheless, we still encounter the problem of an escalating number of SKUs.

6) Lack of advanced SPP tools and techniques

In the past, SPP has not gotten as much attention in academia and industry as manufacturing. Existing SPP systems revolve around spreadsheets, rules of thumbs, and borrowed techniques from production (e.g., MRP, ABC analysis, EOQ, etc.), which may not be optimal in the service parts context. The limited knowledge and its application is an obstacle to effective SPP. In recent years, we have seen some software vendors (e.g., i2 Technologies and Servigistics) providing comprehensive SPP solutions. These cutting edge software systems perform inventory planning, event monitoring, exception alerting and handling, budget optimization, scheduling, and so forth. Network design capabilities have so far been simplistic, and deal with the positioning of FSLs to satisfy the response time constraints of its installation base, without inventory positioning and delivery cost considerations.

7) Outsourcing of service parts services

There is a growing trend to outsource warehousing and transportation of service parts operations through 3PLs, which have greater logistical expertise and advantage of economies of scale and scope. This is especially relevant to companies with customers scattered around the continent. Because demand could arise from almost any state, servicing critical parts (e.g., 2 hrs response time) necessitates stocking spare parts in FSLs in the nearby vicinity of every installation that has such a service contract. Such huge infrastructure outlay is prohibitive to most companies, except for the larger companies.

Contract manufacturers like Solectron have extended their product offerings by providing SPP for its customers. This is especially applicable to small companies that want to focus on their competitive advantage (e.g., technology innovation), and/or do not have the expertise and scale to implement their own SPP systems.

Nonetheless, because good SPP involves fostering relationships with the clientele, training technicians, understanding product design, and many other functions, outsourcing itself is a challenge as 3PLs and clients have to share information and work very closely on the partnership.

Despite the challenging business environment, recent advances in information technology and warehouse management have made real-time parts visibility achievable, which is critical for successful service parts fulfillment and planning. The speed and reliability of package delivery systems have also improved remarkably in recent years. Thus, now we are in a better position to build an effective SPP system.

1.3 Framework for Service Parts Planning

It is useful to study SPP from a functional perspective by breaking it down into a few components. The primary components in a SPP system are: forecasting, network design, inventory optimization, and fulfillment. As seen in Figure 2, these components are part of the business workflow, and are each performed at varying frequency because of the differing granularity of decisions made.

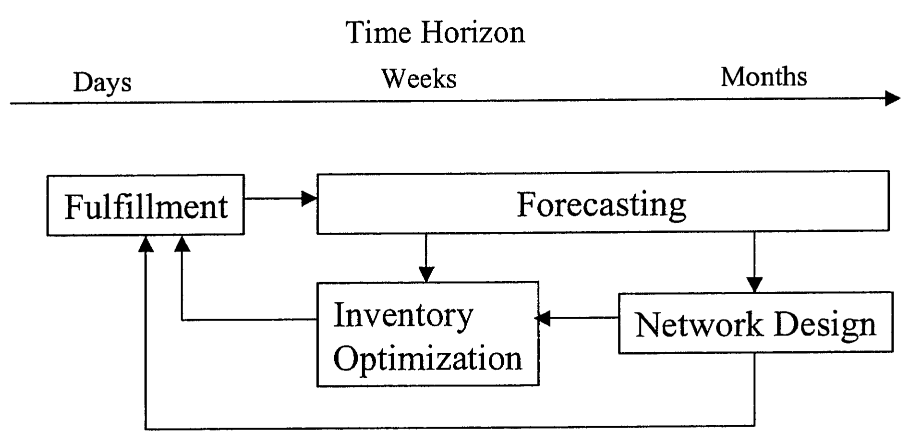

Figure 2. Service Parts Planning Components.

Decisions can range from the execution level where we decide which technician to dispatch immediately to resolve a customer problem, to the planning level where we decide how big a new FSL to build to meet projected demand in the next few years. The resources and information managed at each component are different, and it provides for natural departmental boundaries in an organization. We delve into the details of each component in the subsequent sections.

1.3.1 Forecasting

The forecasting step uses collected order history data, together with manufacturer's specifications, installation base, etc., to determine demand characteristics. Forecasts are never exact, but are essential to planning. However, we can setup safety stocks to safeguard against uncertainties. In Chapter 3, we discuss how forecasting plays a critical role in determining safety stock levels. Nevertheless, a good set of input data and reasonably accurate forecasts are important. There are numerous forecasting techniques available ([24]), and ultimately, we need to derive demand characteristics for each part at a reasonably level of certainty. We can factor part commonality relationships, Mean Time Between Failure (MTBF) rates, and product lifecycles to derive better forecasts. Continuous feedback loops to update forecasts based on recent activity (e.g., order spikes, external reasons) are also effective. Because various forecasting techniques work better under certain kind of demand pattern, we can apply multiple forecasting techniques best suited to the varying characteristics of each part demand. We refer readers to Robeson ([26]) for an excellent coverage on the principles of forecasts, and developing and applying a system for forecasting.

1.3.2 Network Design

Performed less regularly, the network design phase uses forecasted demand data to make long-term infrastructure and distribution decisions, such as where to locate FSLs, how big

FSLs should be, echelon structure, and replenishment systems. These decisions should be aligned with the corporate strategy and result in lower operating costs (transportation, warehouse, inventory, etc.) and achieve predetermined service levels. This is because the day-to-day fulfillment and inventory optimization process depend on the network structure. While the network structure cannot be changed very often, it should be reviewed occasionally to accommodate changes in demand patterns, customer accounts, and so forth. Nevertheless, leases have introduced greater flexibility in network designs, which allow the network to evolve more rapidly to changing operating conditions.

The primary cost drivers are inventory, warehouse, and transportation costs. In general, inventory costs, risk-pooling benefits, and warehouse costs motivate consolidation, while transportation costs and service obligations create deconsolidation incentives. The goal then is to find the best network structure to provide sufficient flexibility and expansibility to serve existing and potential customers.

1.3.3 Inventory Optimization

In this process, we have to make cost effective inventory positioning decisions to best meet demand, subject to capacity constraints and service level obligations. Thus, given the demand characteristics and network structure from the forecasting and network design phase respectively, we can apply optimization techniques to find the optimal inventory position plan. Inventory optimization should be performed regularly to account for changes in accounts, parts, etc. The varying criticality of spare parts, customer service requirements, and transportation cost structure necessitates a different stocking and distribution strategy for each part.

1.3.4 Fulfillment

Fulfillment involves the day-to-day timely delivery of service parts to customers. We refer readers to a case study on the field service operations at IBM ([23]) for a good overview of the operational issues, including communication capabilities and information support. Fulfillment is primarily resources and infrastructure-driven, because it depends on the echelon structure (where FSLs are located and how big) determined during the network design phase, and the inventory stocking plan determined in the inventory optimization process. Available flight routes, inventory levels, field stocking locations (FSL), available technicians, etc. are all fixed. Thus, given these constraints, we have to decide how best to get the spare part from the FSL to the customer. Decisions to make include: from which FSL to pull the part, on which flight to send the part, to which technician to assign the job, the service time window, etc. Unless we have a centralized system, these decisions are most likely made by call center representatives. Some optimization is possible, but time and resource constraints restrict the freedom and available options to fulfill a delivery. Thus, decisions tend to be driven by business rules that are synchronized with prior inventory optimization and network design assumptions. For example, if we have already assigned customers to specific FSLs and allow only parts to be expedited from the central warehouse in stock out situations, then we do not want to compromise the inventory position at other locations by laterally transshipping the part from a neighboring FSL.

Real-time information on part availability, flight routes, technician staffing levels, part tracking, etc. is essential to making informed decisions. The key is to provide the necessary information to the appropriate people and equip them with the necessary decision-making tool or rules of thumb to facilitate timely deliveries.

1.3.5 Summary of SPP components

In this section, we have discussed the key elements of each SPP component (fulfillment, forecasting, network design, and inventory optimization). Although each component performs a different function, SPP's overall effectiveness depends not only on the well-run operation of the individual components, but also the integration and workflow between components.

1.4 Research Objective

In this research, we investigate inventory optimization and facility network design models for service parts. Existing service parts literature, as previously mentioned, has primarily focused on inventory planning, and treated the facility network as given. Little attention has been paid to the impact of strategic facility networks on a company's ability to satisfy customer service obligations effectively and efficiently. While fulfilling service is critical in the service parts industry, companies have to adopt cost cutting measures continuously to improve their profitability. Facility network design presents cost saving opportunities by allowing companies to improve their distribution and stocking strategy. Specifically, companies can optimize the: 1) location and size of warehouses, 2) allocation of inventory among capacitated warehouses, and 3) service area assignments. Cost components include transportation, warehouse, and inventory holding costs.

Thus, the research objective is to use operations research techniques to model and optimize inventory planning and facility networks for service parts. In addition to the challenges in SPP previously mentioned, there are other challenges that arise from mathematical modeling approaches. For example, the scale of service parts operations, which typically deal with hundreds of thousands of parts, pose a significant computational challenge; hence, we need to investigate large-scale computational methods and model aggregation techniques to overcome this challenge. Another challenge is the dependency between inventory policy and facility network decisions. The inventory policy depends on the structure of the facility network, while the design of the facility network depends on the choice of inventory stocking policy, which drives capacity requirements at the warehouse. Moreover, inventory models are typically stochastic, which makes incorporating them in deterministic facility network models particularly prohibitive. Therefore, we investigate simplified methods or models and simplifying assumptions that solve the problem without degrading solution quality excessively.

1.5 Contribution

There are three main contributions of this research:

1) A perspective and method for facility network design in the context of SPP

In existing spare parts planning literature, the stocking points are usually given and have customers pre-assigned to them. Thus, the demand points are the local service centers and warehouses. The goal then is to establish target stock levels to fulfill service level obligations. Instead, we study network design, in which the warehouse location and size are decisions. Sourcing decisions at the FSL-customer level have to be made because it depends on our choice of warehouse location. Factors like demand patterns, fixed and variable warehouse costs, inventory, and transportation costs all affect the network structure.

2) In-depth part characteristic analysis

We investigate the impact of part characteristics (e.g., cost, weight, failure rate) on the optimal distribution strategy. Existing spare parts planning literature tend to focus primarily on the criticality, failure rate, and replenishment lead times in determining the appropriate stocking policies.

3) Modular approach

This research presents another inventory planning approach by separating certain inventory planning decisions. We separate the decisions on how much aggregate inventory to stock throughout the system, and how to allocate this aggregate inventory among the FSLs and central warehouse. This flexibility allows planners to focus on and apply their expertise to different aspects of the problem independently. For example, the planner dealing with how much inventory to stock throughout the system would be concerned more about the product lifecycle, industry trends, part failure rates, and aggregate demand; on the other hand, the planner working on the inventory allocation would have to take into account operational elements such as storage and transportation costs, FSL capacity, etc. This decoupling approach also allows us to gain tractability in our models. Nevertheless, we show in the next chapter that this approach remains effective for the overnight segment.

1.6 Outline of the Thesis

In Chapter 2, we define the problem, explain our motivation, and provide a qualitative overview of the key elements of our solution. Next, in Chapter 3, we discuss the forecasting and safety stock elements of SPP. In Chapter 4, we introduce two models, one is the Uncapacitated Single SKU (USS), and the other is the Capacitated Fixed Charge Multi-SKU (CFCM). In Chapters 5 and 6, we present the concept, apply the relevant model to data provided by a 3PL, and analyze the results for our inventory optimization and facility network processes respectively. Finally, in Chapter 7, we provide conclusions and future research directions.

Chapter 2

2.0 Problem Statement and Solution Overview

2.1 Problem Definition and Scope

As previously discussed, there are many aspects to SPP. An integrative approach that attempts to optimize across all functions of SPP would inevitably be complex; however, by focusing on certain service segments (e.g., 2hr, 4hr, and 24hrs), part characteristics (e.g., low or high volume demand, stable or sporadic demand), and functions of SPP, we can achieve good and tractable solutions. In this research, we address inventory optimization and facility network design for the overnight delivery segment, in which customers require spare parts to be delivered within 24 hours. Specifically, we optimize and answer the following questions:

- What parts and quantity should be stocked at each FSL and central warehouse?
- Where should FSLs be located?
- How big should each FSL be?
- From which FSL should customers in a region be served?
- What kind of distribution strategy (e.g., centralized, decentralized) should be adopted?

We develop mathematical models, and evaluate them with data provided from a 3PL. Our analysis of the model output provides us with insights into the 3PL's optimal distribution strategy. However, these insights are somewhat limited because parts of the data have been altered for reasons of confidentiality and lack of access. The data, nonetheless, is still fairly representative of a typical 3PL's operations. In addition, the research objective is to develop models and validate them, and not to perform exhaustive analysis of data and model output, nor consult for the 3PL. Although simple sensitivity analyses are used in this research, they serve to validate the model rather than to represent actual business scenarios. It is left to the 3PL to setup the necessary data parameters and business cases to extract further insights from the models.

2.2 Motivation

This research is motivated from the study of a 3PL's SPP operations. The 3PL currently provides warehousing and transportation services to its clients, but does not undertake inventory ownership and planning responsibility. An illustration of its operating workflow is depicted in Figure 3.

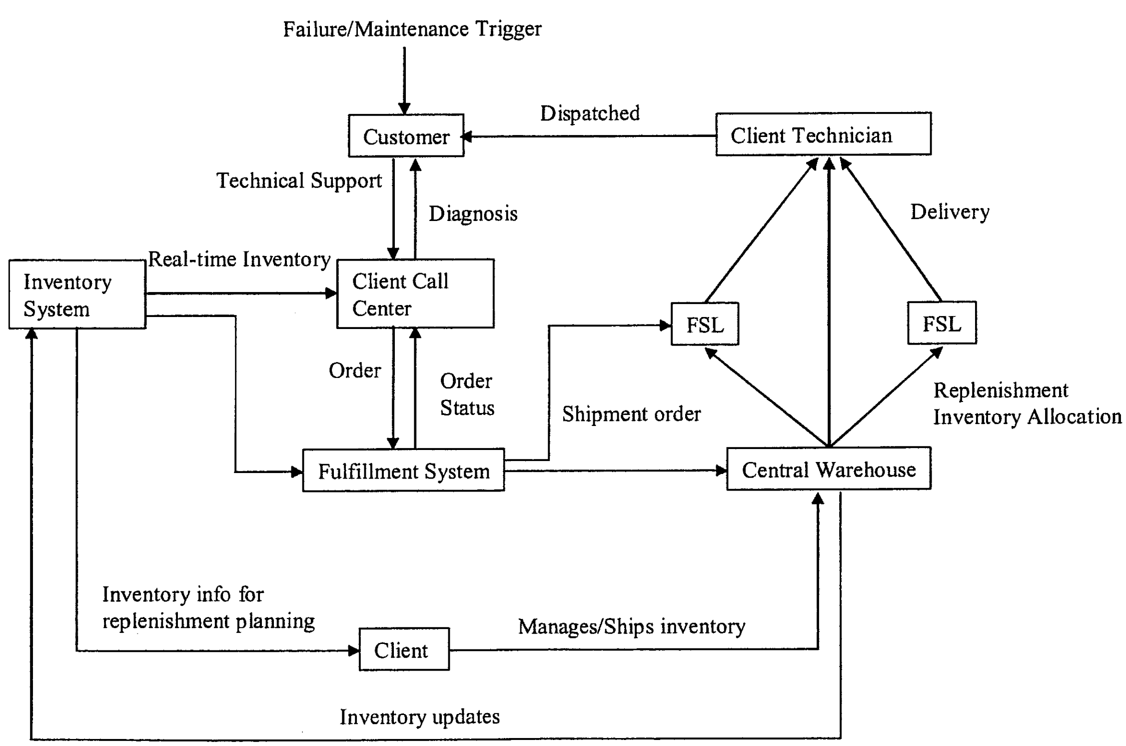

Figure 3. 3PL SPP Workflow Diagram.

When a customer calls the client's call center for a repair or maintenance request, the call center representative attempts to diagnose the problem, and subsequently checks for the availability of spare parts (where it is the 3PL's responsibility to furnish real-time inventory information to its client) and technicians to perform on-site repairs. If the spare parts are available, the representative usually decides from which FSL to procure the part, the mode of delivery (e.g., next day, courier), and which technician to assign the job. The 3PL's role is to deliver the part from its warehouses to either a local FSL for the technician to pick up or directly to the customer location. The client makes inventory stocking decisions, and the 3PL provides the necessary warehouse space and storage handling. The 3PL essentially fulfills the roles of transportation and warehousing for its clients.

While it focuses on the execution and delivery of spare parts, the 3PL has been assessing the potential upsides and its capability to become a one-stop provider of SPP solutions by offering parts planning services. As a 3PL with many client accounts, the number of SKUs involved easily reaches the millions, and the installation base is widely dispersed across thousands of cities. Thus, an important aspect of its SPP solution is scalability. The 3PL should also be able to accurately and quickly quote clients a price for its services, because without an effective tool to assess the impact of adding a new client on its network and distribution operations, the 3PL may run into risks of price misquotes, delivery failures, and future contract changes.

We specifically look at the overnight segment for the following reasons:

1) Constitutes significant portion of delivery volume

Except for the more urgent needs, the overnight delivery can fulfill most customer needs economically. From the survey of companies studied by Cohen et al. ([4]), 70% of them could provide fill-rates of 95% for service responses within 24 hours, while only two companies could provide high fill-rates consistently for its 2-hour service. The overnight segment constitutes slightly more than half its delivery volume for the 3PL; hence it should be a big driver for warehouse location and space requirements.

2) Allows greater freedom in network decisions

Compared to the quicker response services (e.g., 2 and 4 hours), we can exercise greater freedom in network design and inventory positioning for the overnight segment because of less binding time constraints. The quicker services tend to be installation base driven (i.e., we have to stock inventory within certain distance ranges of customers to guarantee response), and companies can usually charge high premiums for such strict service guarantees. On the other hand, we can provide overnight delivery for almost every city pair in the continental U.S. Thus, inventory stock could be strategically centralized if necessary. With the high reliability of package shipment services, high service performance for overnight delivery is assured, and one of the remaining key competitive differentiators is cost. The network should be optimized to ensure the lowest operating costs.

3) Reduces complexity

Recent academic literature has incorporated risk pooling through lateral transshipments in their models. Risk pooling groups are setup whereby nearby FSLs are grouped together, and they share inventory. Thus, if a customer requests a part from a FSL that does not have the particular part in stock, a neighboring FSL in the same risk pooling group as the former FSL, can satisfy the demand if it has stock and can deliver the part to the customer in time. The models, however, tend to be complex and not scalable for the 3PL's size of operations. In the overnight segment, however, we only have one risk pooling group because a part stocked at any FSL can satisfy demand anywhere in the continent. With this simplification, we gain tractability in our model.

Although we have based our research from a 3PL viewpoint, it is equally applicable to companies doing SPP in-house. The degree of aggregation applied varies depending on its scale of operations and availability of computational bandwidth.

2.3 Solution Approach

Formulating inventory optimization and network design models for spare parts is not a trivial task because of the stochastic nature of customer demands and risk pooling, multiple replenishment modes (e.g., lateral transshipments and emergency replenishments) in the distribution echelon, and other complexities. The crux of our models is in the realization of a single risk pooling group in the overnight delivery segment of spare parts, which allows us to separate certain inventory planning decisions to simplify our models. We also deploy techniques like aggregation and part segmentation in a deterministic modeling framework to tackle the large scale nature of the problem. In the following sections, we highlight the various elements of our solution approach.

2.3.1 Single Pooling Group

Because overnight deliveries to any customer location from any FSL is feasible for the 3PL, lateral transshipments are possible; hence, we can define a single pooling group, which mimics a centralized distribution system, where all customer orders are fulfilled from a single bank of inventory. This inventory is determined from all aggregated customer installation demands, and is the minimum total inventory level required to satisfy service level obligations across all customers. After determining the minimum inventory, the next objective is to allocate the total safety stock to the FSLs such that inventory holding, transportation, and warehouse costs are minimized. Additional inventory investment can be made if it results in lower total costs, but we are already guaranteed to satisfy service level obligations with the minimum inventory level. This approach is optimal in the overnight segment because we are adopting a total cost approach. The following graph on cost tradeoff curves between centralized and decentralized systems illustrates the point:

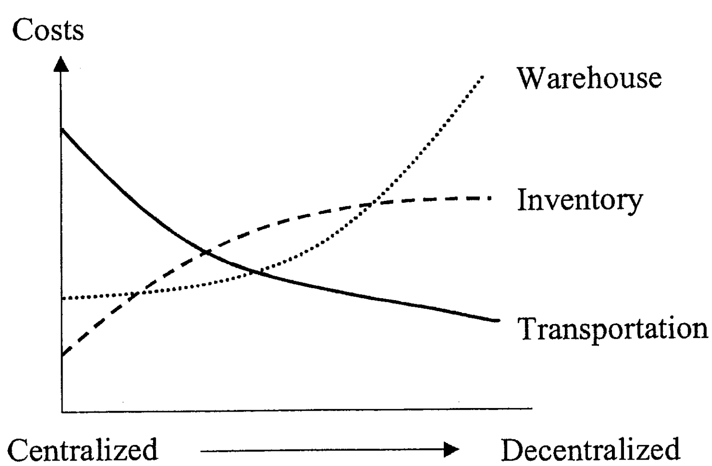

Figure 4. Cost Tradeoff Curves.

The total inventory investment increases when we decentralize. As we elaborate in the next chapter, Eppen ([16]) shows that this is because of the pooling of demands and it has a square-root-like behavior. Essentially, safety stocks are positively correlated to the variability of demand, and demand variability is higher in the decentralized than centralized systems. Warehouse cost is also higher for the decentralized system because of economies of scale and disparity in land costs, especially near metropolitan areas. On the other hand, transportation costs are lower in the decentralized case because cheaper replenishment and delivery modes can be used, as seen in the figure 5 below.

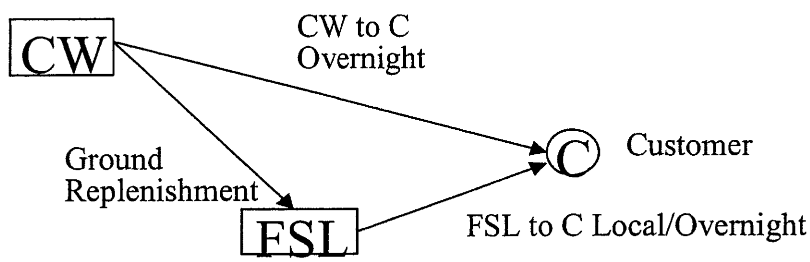

Figure 5. Transportation Replenishment and Fulfillment Structure.

In most cases, the cost to ship a part overnight from the central warehouse directly to a customer is more expensive than the option of using a slower and cheaper replenishment mode (e.g., ground trucking) to ship the part to a local FSL, with the final overnight delivery to the customer via a shorter distance.

Therefore, our approach to determine the minimum inventory level for the single pooling group positions us with the lowest inventory cost possible in a centralized system. We can further optimize the inventory allocation among the FSLs based on inventory holding, transportation, and warehousing costs. We allow for additional inventory investments if they result in lower total costs through better inventory placements. Therefore, by decoupling the total safety stock and allocation decisions in this fashion, we are guaranteed to fulfill service level requirements with the least safety stock, and yet be globally cost optimal.

2.3.2 Part Characteristics Segmentation

Because parts of varying characteristics (e.g., cost, weight, failure rate) exhibit different cost structures, their distribution strategy inevitably vary from part to part. A thorough understanding of the tradeoffs involved in these inventory optimization decisions is critical. These inventory optimization models are the building blocks of the facility network design model, in which we take a holistic approach to determine the necessary capacity and locations of FSLs.

2.3.3 Aggregation

We also gain tractability in our models by aggregation. We need to strike a fine balance between aggregation and tractability because we tend to sacrifice solution quality by too much aggregation, and sacrifice solution time performance by too little aggregation. The presence of numerous SKUs suggests that an aggregation among SKUs of similar characteristics is useful. We aggregate parts along three characteristics: failure rate, part cost, and part weight, to form generic SKUs. Each part falls into a generic SKU group depending on its characteristics. We also use geographic aggregation to reduce the model size and solution times. Thus, instead of modeling cities and specific FSL locations, we aggregate demand and FSL capacities at the state level. This level of detail is sufficient given that we are operating at the overnight level where time is less constraining, and discrepancies between using state-to-state versus zipcode level transportation cost are small enough. In addition, network design tends to focus on the aggregate volumes and capacities instead of the specific and detailed aspects of day-to-day operations.

2.3.4 Deterministic Models

While the academic literature has focused on stochastic models, our emphasis on network design motivates the use of deterministic models, which drastically reduces complexity and allows us to gain solution tractability. This is because deterministic models provide a more natural form of modeling binary decisions (e.g., whether to open an FSL), and certain operations research techniques allows us to solve large scale problems more effectively. Despite the lack of stochastic elements in our models, we show that our models are relevant to the circumstances of the 3PL under study, and capture sufficient detail to generate inventory stocking plans and insights into facility network design.

2.3.5 Data Driven Model

Another key feature of our solution approach is that the models are data-driven. This flexibility allows what-if scenario analysis to be performed, such that the impacts of changes in the demand or network structure (e.g., location and size of FSLs) can be assessed easily. This is particularly useful to the 3PL, because customer accounts grow and change rapidly, and we have to find the optimal or the necessary incremental changes to the distribution network.

Chapter 3

3.0 Demand Forecasting and Safety Stock

3.1 Overview

The purpose of forecasting is to predict future demand patterns, a key data input to inventory planning. Because there is variability in our demand forecasts, we establish safety stocks to protect ourselves from bigger and/or more frequent orders than expected. It is cost prohibitive to stock excessive safety stock, yet we need enough to satisfy customer service levels. Safety stocks are also necessary to protect ourselves from supply delays and volatility. We need to hold less safety stock when we have a reliable and rapid supply of parts. Safety stock is intrinsic to the spare parts industry because the demand for spares is sporadic, and supply lead times tend to be long and uncertain.

We refer readers to Makridaki ([24]) for a wealth of forecasting techniques, and Hillier ([19]) for coverage of inventory policies. Because the choice of forecasting technique and inventory policy could be subjective and vary depending on part characteristics, there is no single best combination of forecast technique and inventory policy. Thus, instead of enumerating the various forecasting techniques and inventory policies, we provide guidelines on the factors that one needs to consider in generating good forecasts and safety stock levels in the service parts industry. We first discuss forecasting techniques, introduce the important concept of risk pooling, elaborate on safety stock factors, and finally show how they apply to our inventory optimization and facility network models.

3.2 Forecasting Techniques

The demand pattern can be characterized by order arrival times and sizes. Though we cannot predict the exact moment of order arrival and size, forecasts are necessary as a baseline for planning. Good forecasts and planning help reduce obsolescence and unwanted inventory investments, and ensure that service obligations can be met cost effectively. Future demand patterns can be predicted empirically, theoretically, or both. Empirical methods require historical data for each particular SKU or another SKU of similar characteristics. The latter applies especially for new products where no historical demand data exists, and David ([30]) shows that analytical methods could be more favorable than pure estimates. Methods range from simple moving averages to exponential smoothing ([24]). The common theme in these empirical methods is the continuous update of forecasts as new data becomes available. On the other hand, theoretical methods involve understanding the product's failure characteristics and sizing the installation base. Manufacturers sometimes provide Mean Time Between Failure (MTBF) specifications for components, and from renewal theory, we can derive failure distributions for the product and components. Ironically, MTBF statistics are usually determined from empirical tests. The volume of demand is proportional to the existing number of installations. Such data, however, is often not available. In such cases, product lifecycle analysis can be useful. For example, there is usually a point where supporting almost obsolete equipment is more costly than upgrading it. There are also many other factors that can affect demand like product usage behavior, seasonality and climate effects, and so forth.

It is sometimes useful to express demand patterns with statistical distributions. The distributions provide us with the range of number of failures and associated probabilities, for a given time frame. The Poisson distribution is most commonly used in the spare parts industry. It is an approximation to the Binomial distribution:

$$f(x) = {}^{n}C_{x} \lambda^{x} (1-\lambda)^{n-x}, \tag{3.1}$$

where f(x) is the probability density function (PDF) for the number of failures, x, with total number of samples, n, and failure rate, λ. For large values of n, however, the combination function, $^{n}C_{x}$, gets increasingly computationally expensive. The Poisson distribution is an approximation to the Binomial distribution for small values of p, which applies to the spare parts industry where failures are infrequent. The PDF for the Poisson distribution is as follows:

$$f(x) = \frac{e^{\lambda} \lambda^{x}}{x!} \tag{3.2}$$

The sporadic nature of spare parts demand is the biggest challenge to forecasting. There is no correct forecasting method, and some methods work better for certain parts but not others. Instead, a variety of combinations of empirical and theoretical methods adjusted with fudge factors (e.g., human adjustment, other causal factors, industry trends, externalities, etc.) might work best.

3.3 Risk Pooling

Risk pooling is a method to reduce risk by aggregating a set of random outcomes. In SPP, through increased demand aggregation by pooling customers together, we experience less demand variability, which translates to less risk in fulfilling service performance targets. From an inventory policy perspective, less safety stock is required. Intuitively, because demands are not perfectly correlated, the positive and negative demand fluctuations tend to cancel each other. The negating effect of the demands reduces the variability of aggregated demand. An example would be useful to describe the benefits of risk pooling. Consider having a single centralized warehouse instead of two separate decentralized warehouses to serve customers A and B (see Figure 6).

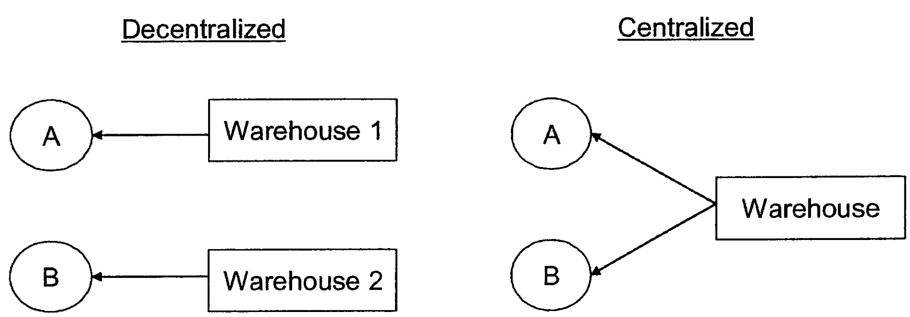

Figure 6. Risk Pooling Example.

The following table shows the demand characteristics of the two independently distributed customer demands (A and B) and aggregated demand within a certain time period, and also the computed safety stock requirements:

Customer Demand	Mean	Standard Deviation	Safety Stock Required
A	10	3	19
B	15	4	27
A and B (aggregated)	25	5	40

Table 1. Customer Demand Characteristics for Risk Pooling Example.

The characteristics of the aggregated demand are calculated using statistical methods, and safety stock requirements are determined by covering three standard deviations of demand plus the expected demand during the time period. For example, for customer A, the safety stock required 19, which is three standard deviations, 9, plus the mean, 10. In the decentralized case, a total of 46 units (19+27) units of safety stock are required, while only 40 units are needed in the centralized case. This illustrates the potential inventory savings by aggregating demands.

Riskpooling has a statistical origin, where the standard deviation of a sum of independent and identical (i.i.d.) random variables is the square root of the sum of the variance of each random variable. Suppose we have n customer demands with distributions $D_1, D_2, \ldots, D_n$. With a single stocking location to serve all customers, then the standard deviation of aggregated demand is:

$$\begin{aligned} Stdev(\sum_{\forall i} D_i) &= \sqrt{Var(\sum_{\forall i} D_i)} \\ &= \sqrt{\sum_{\forall i} Var(D_i) \quad + \quad 2\sum_{j<k} Cov(D_j D_k)} \end{aligned} \tag{3.3}$$

Under i.i.d.conditions, the covariance term is zero. Thus,

$$Stdev(\sum_{\forall i} D_i) = \sqrt{\sum_{\forall i} Var(D_i)} \tag{3.4}$$

The square root term is the gist of risk pooling, because the square root of a sum is smaller than the sum of the square roots. Thus, the combined standard deviation is less than the sum of the standard deviations of the random variables. In the case of disaggregated demand, our total standard deviation is:

$$\sum_{\forall i} Stdev(D_i) = \sum_{\forall i} \sqrt{Var(D_i)} \geq \sqrt{\sum_{\forall i} Var(D_i)} = Stdev(\sum_{\forall i} D_i)\,. \tag{3.5}$$

The inequality in equation 3.5 holds under positive elements in the square root, which is true in our case because variances are always positive.

Therefore, as shown statistically, we encounter less demand variability when demands are aggregated as much as possible. This means serving as many customers as a single stocking location can support. Such a centralized stocking strategy yields the lowest possible safety stock investment.

3.4 Safety Stock

3.4.1 Factors

As previously mentioned, safety stock is necessary in SPP, and the level of safety stock depends on the following:

1) Service level performance

There are many benchmarks for service level performance. The typical measure is the fill-rate, but there are many interpretations depending on the company's or 3PL's role. It could be the probability of having the part in the FSL when an order arrives, or the probability of delivering the part to the customer within a certain amount of time. First time fix rates are also important because minimizing downtime is of utmost concern to many customers. Companies can achieve higher service levels by positioning more of the right parts at the right places. Because of demand uncertainty, this means holding more safety stock and placing them closer to their customers.

Customers that cannot afford expensive downtimes or potential life hazards often demand quick response and more binding guarantees of on-time delivery. For such critical parts, higher safety stock levels should be established.

2) Customer demand pattern

For a given service level, the more volatile the demand, the more safety stock required. The safety stock is necessary to guard against unexpected demand spikes. The volume and dispersion of customers also play an important role in determining appropriate safety stock levels because of risk pooling effects. High customer concentration in a particular region allows for more demand aggregation, which decreases the variability of total demand. Safety stocks are usually established to cover sufficient demand levels such that the cumulative probability of satisfying demand is at least equal to the desired fill-rate. For Gaussian distributions, the spread is proportional to the standard deviation; hence, safety stocks follow standard deviations very closely, and aggregated demands can enjoy inventory savings over disggregated demands.

3) Supplier availability of parts and lead time duration and volatility

Just as we respond to uncertainty in demand with safety stocks, supply uncertainty requires the same treatment. If lead times are long, then we need to hold more safety stock to cover demands that arrive within the replenishment cycle time. Similarly, more safety stock is required if supply lead times are volatile. In the case that availability of the part will be scarce or nonexistent, the company can make a last-time buy decision, where as much inventory to cover future demand should be procured.

4) Ordering policies

The inventory policy used affects the safety stock levels. Examples include: the commonly used one-for-one (S-1, S) policy where we order a part replenishment for every part delivered to the customer; min-max (s, S) policy where we replenish the safety stock when it reaches a predetermined reorder point; and fixed replenishment (Q, R) policies where replenishments follow a fixed schedule. The various inventory policies can be applied to different demand profiles. For example, the one-for-one (S-1, S) policy can be applied to parts with low demand, while the min-max (s, S) policy is suitable for parts with less demand variability.

5) Obsolescence

Towards the end of the product lifecycle, the incentives of stocking the part decrease because the number of customer installations dwindles. Obsolescence bears a huge cost to the service parts industry, and safety stock is the root of the problem. We need to strike a balance between absorbing high obsolescence costs versus the loss of service to the remaining customers.

3.4.2 Inventory Policy

We illustrate how some of the above factors come into play through the min-max (s, S) inventory policy ([31]). To facilitate our discussion, we introduce the following notation:

AVG = Average daily demand.

STD = Standard deviation of daily demand.

L = Constant replenishment lead time.

H = Cost of holding one unit of the product for one day.

α = Service level or fill-rate. This implies that the probability of stocking out is $1-\alpha$.

K = Fixed ordering cost.

The inventory policy consists of a reorder point (s) and order-up-to-level (S), as depicted in Figure 7.

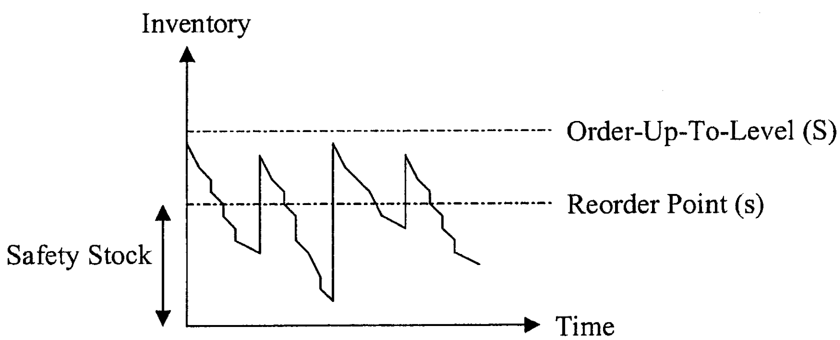

Figure 7. Min-Max Inventory Policy.

The reorder point has two components: 1) average inventory during lead time, which is the product of average daily demand and the lead time, to ensure sufficient inventory until the next order arrives; 2) safety stock, which is the amount of inventory needed in the warehouse and pipeline to protect against deviations from average demand during lead time. Thus, the reorder point (s) is:

$$s = L \times AVG + z \times STD \times \sqrt{L} \quad , \tag{3.6}$$

where z is chosen from the standard statistical distribution to ensure that the probability of stockouts during the lead time is 1-α. It must satisfy the condition:

$$probability\{demand\ during\ lead\ time \geq L \times AVG + z \times STD \times \sqrt{L}\} = 1 - \alpha \tag{3.7}$$

In the absence of fixed ordering costs, the order-up-to-level is the same as the reorder point, and we order whenever the stock dips below the reorder point. With fixed ordering costs, however, we tend to order in batches to reduce ordering costs; hence, the order-up-to-level might be higher than the reorder level. An Economic Order Quantity model (EOQ) can be used to determine the optimal order size, Q. Thus, the order-up-to-level is:

$$S = \max\{Q, L \times AVG\} + z \times STD \times \sqrt{L} \tag{3.8}$$

The commonly used (S-1, S) policy for service parts is a variation of the (s, S) policy where the reorder point (s) is one unit less than the order-up-to-level (S). Thus, we order from the supplier the moment a demand arrives. This is similar to the above mentioned case with no fixed ordering costs. The rationale behind the (S-1, S) policy for spare parts is the criticality of maintaining the safety stock level at all times to protect against unexpected demand.

In the case of near obsolete parts or supplier discontinuations, we can use a single period Newsboy model to optimize last time buys. It includes factors like the penalty of stocking out and scrap value. For details of the model, we refer readers to Winston ([34]).

As in forecasting methods, safety stock calculations can also be an art. Currently, there is no single best inventory policy, and parts with varying demand profiles may require different methods. By fine tuning these methods based on historical performance and projecting future demand patterns, we can attempt to seek greater convergence between plans and reality.

3.4.3 Shortcomings

There are two major issues with existing inventory policies for spare parts:

1) Coverage during lead time concept

Setting safety stock according to supplier replenishment lead time works for more stable demand volumes (such as in production and certain retail systems), but not necessarily for service parts, where demand is sporadic. The rationale for the lead time concept is that replenishments can only arrive after a certain lead time, and during that time, the stock is subject to any demand. By setting up a fill-rate target, we can expect to satisfy a certain percentage of orders during lead time. Most service parts literature and applications have taken the same approach. Unfortunately, this approach works well only for demand of low to moderate variability. Although valid in a statistical sense where we can expect the fill-rate to be achieved, it applies only in the long run expectations. It is not representative of actual service parts operating conditions, where demand variability tends to be high, and can be misleading when calculating the required safety stock. It provides too little margin for forecasting errors. During the replenishment lead time, sporadic demand patterns can easily overwhelm the safety stock.

2) Customer held safety stock

Customers usually hold their own safety stock for very critical components or for precautionary reasons. Thus, they have their own inventory system and tend to order in batches. Order batching introduces forecasting problems for the supplier when customer order patterns are unknown. For example, if there are five demands of two units in a year, then the daily mean is 0.0274. A typical week-long replenishment lead-time means that we expect 0.192 units with equal variance (according to the Poisson distribution). Three standard deviations of stock (1.315 units) to cover 99% of demands cannot satisfy the potential demands of two units. We cannot establish a reasonable safety stock level based on this information. Unless we know and model the customer's inventory levels and ordering patterns, alternative forecasting and inventory policies need to be investigated. While batch ordering offers certain economies of scale advantages, the service performance and forecasting accuracy benefits of one-for-one over batch replenishments should be studied to determine the appropriate ordering policy. In the case of low volume and sporadic demand, the one-for-one policy should be more favorable, and has been widely accepted by the majority of service parts literature.

3.5 Application

The unique conditions of the overnight segment allow us to establish one single pooling group throughout the continental U.S.; hence, we can aggregate all demands. Then, our objective is to determine the minimum inventory level for each part subject to the factors previously discussed. While we do not delve into the details or conjure a perfect forecasting solution for the service parts industry, we provide a framework for using such data in the subsequent inventory optimization and facility network design steps. We have decoupled the total safety stock decision from the optimization algorithms. This allows flexibility in selecting appropriate forecasting tools and inventory policies without losing integrity of our optimization models.

Chapter 4

4.0 Optimization Models for Inventory Optimization and Facility Network Design

4.1 Models Overview

We use two basic models in our analysis of inventory optimization and facility network design. They are the Uncapacitated Single-SKU (USS) and Capacitated Fixed Charge Multi-SKU (CFCM) models. The USS model determines the optimal stocking solution for a single part based on cost parameters and service constraints. The CFCM model introduces capacity constraints and fixed warehouse costs, and optimizes across all SKUs.

4.2 General Assumptions

The following assumptions apply to both models, and assumptions specific to a particular model are discussed separately:

1) Availability of overnight service

We assume that overnight service is available for any origin-destination pair in the continental U.S. Although it may not be true for very remote locations, the installation base in such regions is probably very small or nonexistent, and unlikely to have the commercial need for overnight service.

2) Installation base

Because of lack of installation base data for each region, we represent it as a percentage of population in that region. Commercial activity data would also be a good indication of installation base, but we use population data for its simplicity and accessibility. The installation percentage, however, is also unknown; but we can adjust the installation percentage and failure rate (number of failures per installation per year) to match the expected number of failures in a year. By fixing the installation percentage value, we can classify each part into a particular failure rate category based on its expected annual number of failures. Nevertheless, the model can handle the installation base data, if made available.

3) Transportation costs

In our datasets, demands and FSLs are aggregated to the state level. Transportation costs, however, are rated at the three-digit zip code level. Thus, we used a weighted average of transportation cost based on the proportion of population in that three-digit zip code with respect to the statewide population. This is reasonable because the delivery volume is greater for more dense installation bases.

4) Independent and identically distributed (i.i.d.) demands

We assume that demands for a part are independent and identically distributed. Thus, the failure of a part is independent of others. This may not apply when demands are correlated under external conditions, such as a citywide blackout, earthquakes, and so forth.

5) Low stock out rates

In our model, we assign customers to FSLs, and compute transportation costs based on that assignment. Although we can show that the minimum inventory distributed among the FSLs is sufficient to satisfy assigned demand with high fill-rates, there is still a small probability that demand has to be satisfied from another FSL during replenishment lead times. In such cases, we incur a different transportation cost. This assumption is reasonable because of the low probability associated with such a situation, and the additional transportation cost from shipping from a nearby state is small. Nevertheless, service level targets are still satisfied as we can overnight a part to a customer from any FSL.

6) Supplier replenishments

We assume that suppliers replenish parts directly to the central warehouse. Although it may be cheaper to ship the parts to certain FSLs closer to the supplier, it increases the amount of coordination required. The models, however, can handle direct supplier replenishments to FSLs by altering the transportation cost structure.

7) Storage capacity

Storage capacity can be difficult to express because of the varying layout and height of the facility, as well as the availability of storage racks and handling equipment. This results in different space utilization rates across the FSLs and central warehouse. For the sake of simplicity of our analysis, we assume that the storage capacities are proportional to the square footage area of the FSLs and central warehouse.

Another issue is that the overnight segment competes for capacity with the faster response segments: two and four hour time windows. We assume that the maximum amount of allocated capacity at each FSL and central warehouse for the overnight segment is known. One approach to handle this assumption is a layered planning method by planning for inventory at the FSLs for the quicker responses first, and provide the remaining capacity to the overnight segment.

4.3 Inventory Optimization Model

4.3.1 Overview

We introduce the Uncapacitated Single-SKU (USS) model is to determine an optimal part stocking plan by minimizing inventory holding and transportation costs subject to satisfying FSL capacity constraints and service level obligations. Service level obligations have already been explicitly incorporated into the minimum inventory level; hence, they will always be satisfied. We first introduce the notation accompanied by brief explanations, followed by the mixed-integer program.

4.3.2 Notation

<u>Sets</u>

Z – Set of all customer regions. The regions can be at the city level, 3-digit zip code, 5-digit zip code, state, or any user defined boundaries. The level of detail will affect solution runtimes.

W – Set of all existing Field Stocking Locations (FSL) and central warehouses (CW). Similar to customer regions, we can use aggregation to group smaller nearby FSLs together.

Parameters

t_{ij} – Unit transportation cost of serving customer region i from CW/FSL j. It includes replenishment cost from the CW at ground rates, and fulfillment cost from the FSL to the customer region at next day rates.

$invc_j$ – Unit inventory holding and warehouse cost across the time horizon at CW/FSL j. It includes cost of capital, warehouse storage, leasing, insurance, tracking, handling, obsolescence, etc. Inventory holding cost varies across FSLs because of their unique cost structures.

qty_i – Number of installations in customer region i.

Mininv – Minimum inventory level to achieve desired service level performance. This value is determined from the forecasting and safety stock calculations discussed in the previous section.

s – Sharing ratio of number of installations to part. It is calculated by taking the total number of installations divided by the minimum inventory level. The ratio ensures a fair share of inventory, such that each installation is subjected to the same stock out rate at its assigned FSLs, and a single part is not shared by an excessive number of installations. It can be fractional.

$usage_i$ – Usage (failure) rate of the part in customer region i within the time horizon. It is the expected number of times we have to deliver the part to an installation in the time horizon. It is region specific to allow flexibility to model high intensity failure zones.

Note that the transportation and inventory costs need to be in the same time frame. If we consider annual inventory holding costs, then the transportation cost has to reflect the expected number of shipments in a year.

Decision Variables

X_{ij} – Fraction of demands in customer region i serviced from CW/FSL j. It is fractional to allow multiple sourcing of customer demands.

Yj – Number of parts to stock at CW/FSL j. It is an integer value as parts are discrete.

4.3.3 USS Mixed-Integer Program

$$
\begin{array}{llll}
\textit{Minimize} & \sum_{\forall i}\sum_{\forall j} usage_i qty_i t_{ij} X_{ij} + \sum_{\forall j} invc_j Y_j & & (4.1) \\
s.t. \quad \textit{Cover}) & \sum_{\forall j} X_{ij} = 1 & ,\forall i \in Z & (4.2) \\
\textit{Sharing}) & \sum_{\forall i} qty_i X_{ij} \le sY_j & ,\forall j \in W & (4.3) \\
\textit{Forcing}) & X_{ij} \le Y_j & ,\forall i \in Z, \forall j \in W & (4.4) \\
 & 0 \le X_{ij} \le 1 & & (4.5) \\
 & Y_j \ \textit{Integer} \in [0, \textit{Mininv}] & & (4.6)
\end{array}
$$

The objective function (4.1) minimizes transportation costs and inventory holding costs. Cover constraint (4.2) ensures that all demand in each customer region has been assigned to FSLs. Sharing constraint (4.3) ensures that parts are sufficiently stocked at each FSL to serve its assigned customer region, and implicitly constrains the model to stock at least the minimum amount of inventory. For example, if there are 100 installations and minimum inventory is 5, then the sharing factor is 20. Because constraint (4.3) ensures that each unit of stock is sourced to no more than 20 installations, and constraint (4.2) requires all 100 customer installations to be served, the minimum inventory level requirement of 5 units would implicitly be enforced. Forcing constraint (4.4) serves to strengthen the LP bound. Constraints (4.5) and (4.6) respectively bind the range of values of the decision variables.

The outputs of this model are the total cost, amount of inventory to stock at each FSL, and the customer region to FSL service assignments.

4.4 Facility Network Models

4.4.1 Overview

Modeling of facility networks introduces additional level of complexities because we not only have to incorporate the planning of every SKU simultaneously, we have to account for how the capacity is shared among the SKUs and fixed warehouse cost economics. In this section, we first examine an extension of the USS model to accommodate capacity constraints, fixed warehouse costs, and all parts, and demonstrate that it is an intractable approach in the operational context of the 3PL. Then we discuss how we can modify the data setup, model formulation, and solution algorithm, to achieve a workable model – the Capacitated Fixed Charge Multi-SKU (CFCM) model.

4.4.2 USS Extension Model

The USS model handles only a single SKU, and we can extend the model to consider multiple parts simultaneously by using part specific variables (e.g., transportation cost, usage, installation quantity, etc.) and including capacity linking constraints. By subscripting all parameters and decision variables defined in section 4.3.2 for the USS model with a part specific index, k, we are essentially overlaying one USS model on top of another, for all parts. We also introduce the following additional notation:

<u>Sets</u>

P – Set of all SKUs.

<u>Parameters</u>

F_j – Fixed cost of opening and operating FSL/CW j. The fixed cost should be considered in the same time frame as the other cost components. In the annual case, it can be the annual leasing cost or an amortized investment.

Cap_j – Maximum capacity of FSL/CW j. It can be expressed in cubic feet or some other unit of volume measure (e.g., number of pallets, racks).

V_k – Volume of SKU k.

<u>Decision Variables</u>

Z_j – Binary decision variable that has value 1 if FSL j is open; 0 otherwise.

The formulation for the USS extension model is as follows:

$$\text{Minimize} \quad \sum_{\forall i}\sum_{\forall j}\sum_{\forall k} usage_{ik}\, qty_{ik}\, t_{ijk} X_{ijk} + \sum_{\forall j}\sum_{\forall k} invc_{jk} Y_{jk} + \sum_{\forall j} F_j Z_j \tag{4.7}$$

$$s.t. \quad \text{Cover)} \quad \sum_{\forall j} X_{ijk} = 1 \qquad , \forall i \in Z, \forall k \in P \tag{4.8}$$

$$\text{Sharing)} \quad \sum_{\forall i} qty_{ik} X_{ijk} \le s_k Y_{jk} \qquad , \forall j \in W, \forall k \in P \tag{4.9}$$

$$\text{Capacity)} \quad \sum_{\forall k} V_k Y_{jk} \le Cap_j Z_j \qquad , \forall j \in W \tag{4.10}$$

$$\text{Forcing)} \quad X_{ijk} \le Y_{jk} \qquad , \forall i \in Z, \forall j \in W, \forall k \in P \tag{4.11}$$

$$0 \le X_{ij} \le 1 \tag{4.12}$$

$$Y_j \ \textit{Integer} \tag{4.13}$$

$$Z_j \ \textit{Binary} \tag{4.14}$$

Objective function (4.7) minimizes the transportation, inventory holding, and fixed warehouse costs. Similar to the USS model, cover constraint (4.8) ensures that all demand in each customer region has been assigned to FSLs. Sharing constraint (4.9) ensures that parts are sufficiently stocked at each FSL to serve its assigned customer region, and implicitly constrains the model to stock at least the minimum amount of inventory. Capacity constraint (4.10) is a linking constraint between the parts, and sets the capacity volume limit at each FSL. Forcing constraint (4.11) serves to strengthen the LP bound. Constraints (4.12) to (4.14) bind the range of values of the decision variables.

The number of constraints (|Z||P| + |W||P| + |W| + |Z||W||P|) and variables (|Z||W||P| + |W||P| + |W|) increases rapidly with the number of parts, customer installations and FSLs. In a reasonable situation that we have 100,000 parts, 100 FSLs, and 1000 customer regions, the model would have over 10 billion constraints and variables each. Because the parts share the same network of FSLs and central warehouse, and compete for limited storage space at strategic locations, we can expect computational requirements to increase exponentially as the number of parts increases. Considering the 3PL's role of managing many customer accounts, the number of parts could easily reach the millions, rendering the model intractable. In the next section, we discuss how our solution approach in the CFCM model can mitigate these computational challenges.

4.4.3 Capacitated Fixed Charge Multi-SKU Model (CFCM)

4.4.3.1 Overview

The scale of the 3PL's operations introduces computational challenges, which can be overcome using various data setup, model formulation, and solution algorithm techniques. By creating representative generic SKUs and aggregating data, we can drastically reduce the model size. The model can also be reformulated using composite variables, which Cohn ([12]) shows to be effective for modeling large scale problems. We then use a branch-and-price algorithm, surveyed by Barnhart et al. ([3]), to gain tractability in solving these large-scale integer programs. In this section, we delve into the various components of our solution approach and discuss the model formulations.

4.4.3.2 Generic SKUs

As previously discussed, the model becomes intractable when we have millions of parts. We can, however, establish a few generic SKUs based on varying part characteristics (e.g., weight, cost, failure rate), and consolidate the real parts into these generic SKU groups. Although a perfect fit into the exact part characteristics of a group is rare, it suffices to approximate real parts that have similar characteristics. For example, a 15lb part that costs $75 and fails on average three times per year might be classified into the generic SKU group of 10lb parts of $100 value and fails on average 5 times per year.

The motivation for this approach is that a lot of parts are similar, and they generate the same optimal distribution strategy. Thus, instead of modeling a certain kind of part several times, we can simply use a single generic SKU.

4.4.3.3 Aggregation

Aggregation serves two main purposes: 1) to improve solution time performance by reducing model size; 2) to reduce forecast errors by pooling uncertainty. However, it comes at a price of loss of solution detail. In the large scale systems for service parts, aggregation is imperative. We need to strike a good balance of aggregation and solution detail. Simchi-Levi ([31]) provides a guideline for aggregation of demand, customer region, and product groups to reduce forecast errors, and maintain solution tractability and quality. In our datasets, we used:

- 49 U.S. states for demand regions (excluding Alaska, Guam, Hawaii).
- 47 FSL locations.
- 64 generic SKUs for product groups.

Because transportation costs are provided by a major package carrier at the 3-digit zip code level, a population and FSL capacity weighted average was used to determine the origin (FSL) to destination state shipping costs.

We found the aggregation level suitable from both solution quality and computation performance perspectives. Subject to the availability and performance of computation resources, we can introduce more generic SKU groups to reduce the approximation errors associated with categorizing real parts into these generic SKU groups.

4.4.3.4 Composite Variables

To further improve model performance, we adopt a composite variable approach ([12]). Instead of explicitly deciding on the assignment of customers to FSLs as seen in the USS extension model, we formulate the composite decision variable as a part stocking solution, which consists of the number of units of a particular part stocked at each FSL and the customer assignments to those units. In so doing, we exclude the individual part's assignment and stocking decisions from the problem. The number of constraints in our model ($|P| + |W||P| + 2|W|$) is reduced to 3166 for the model size specified in section 4.4.3.3. In the next section, we introduce the CFCM composite variable model.

4.4.3.5 Formulation

In addition to the notation introduced in section 4.3.2 for the USS model and section 4.4.2 for the USS extension model, we have the following additional notation for the CFCM model:

<u>Sets</u>

P – Set of all generic SKUs.

S^k – Set of stocking solutions for generic SKU k.

<u>Parameters</u>

C_{fk} – Cost of selecting stocking solution f for generic SKU k. This consists of the transportation and inventory holding cost.

V_{fkj} – Volume requirement for stocking solution f for generic SKU k at FSL/CW j. This is computed from the number of parts stocked in the solution f at the FSL/CW multiplied by its volume.

δ_{fkj} – Indicator equal to 1 if solution f for generic SKU k uses FSL/CW j; and 0 otherwise.

N_k – Number of real parts fitting generic SKU k characteristics.

Decision Variables

G_{fk} – Fraction of real parts of generic SKU k that use stocking solution f. It is fractional so the real parts in a generic SKU category can adopt varying stocking solutions.

Z_j – Binary decision variable that has value 1 if FSL/CW j is open, otherwise 0.

We formulate the CFCM problem as a set-partitioning LP with side constraints:

$$\begin{array}{llll}
\textit{Minimize} & \sum_{\forall f}\sum_{\forall k} C_{fk} N_k G_{fk} + \sum_{\forall j} F_j Z_j & & (4.15) \\
\textit{s.t.} \quad \textit{Convexity}) & \sum_{\forall f} G_{fk} = 1 & , \forall k \in P & (4.16) \\
\textit{Forcing}) & \sum_{\forall f} \delta_{fkj} G_{fk} \le Z_j & , \forall j \in W, \forall k \in P & (4.17) \\
\textit{Capacity}) & \sum_{\forall k}\sum_{\forall f} V_{fkj} G_{fk} N_k \le Cap_j Z_j & , \forall j \in W & (4.18) \\
& Z_j \ \textit{Binary} & , \forall j \in W & (4.19)
\end{array}$$

In the objective function (4.15), we minimize fixed warehouse costs plus the stocking costs (inventory holding and transportation) across all parts. Convexity constraint (4.16) ensures that all real parts in each generic SKU group has been designated a stocking solution. Forcing constraint (4.17) requires the FSL to be open if any stocking solution selected uses that FSL. Capacity constraint (4.18) places volume restrictions on the number of parts that can be placed at each FSL. Constraint (4.19) ensures that the decision variable takes on value 0 or 1.

The number of composite variables, G_{fk}, can be very large if we were to enumerate all feasible stocking solutions. For example, if we were to consider stocking five units of a certain SKU among 100 FSLs, then we have a total of 100^5 possible stocking combinations. While we can try generating good candidate stocking solutions to reduce solution time, we are compromising on solution quality by possibly depriving the model of certain stocking solutions. In the next section, we discuss a solution algorithm that can overcome this problem.

4.4.3.6 Solution Algorithm

The branch-and-price technique ([3]) is useful for solving very large integer programs. It is the branch-and-bound method in which bounds are determined using column generation to solve the LP relaxations at nodes of the branch-and-bound tree. At each node, instead of enumerating all the columns, we solve a master problem with a restricted set of variables, or columns. Then we run a pricing problem, in which the goal is to generate new variables with negative reduced cost. If such columns are found, we introduce them into the restricted master problem. We iterate between solving the master and pricing problems until no negative reduced costs are found, at which time we have an optimal solution to the LP relaxation of the master problem, and we stop generating columns for that node. The solution times depends on how quickly the pricing problem runs, and the quality of new reduced cost columns (stocking solutions) introduced into the master problem.

The branch-and-price framework can be applied to our problem. The CFCM model previously described constitutes the master problem, and the columns are the composite variables. In addition, instead of enumerating all feasible stocking solutions in the master problem, we can formulate a pricing problem, as detailed in the next section, in which new variables (stocking solution) that improve the objective function are generated and introduced into the restricted master problem.

4.4.3.6.1 Pricing Problem

The pricing problem generates optimal part stocking solutions based on modified reduced costs. We use the duals from the master problem to compute the reduced cost of any variable:

<u>Duals</u>

σ_k – Dual associated with convexity constraint (4.16)

π_{jk} – Dual associated with forcing constraint (4.17)

ρ_j – Dual associated with capacity constraint (4.18)

$$\begin{aligned}\overline{C_{fk}} &= C_{fk}N_k - \sigma_k - \sum_{\forall j \in W} \delta_{fkj}\pi_{jk} - \sum_{\forall j \in W} V_{fkj}N_k\rho_j \\ &= C_{fk}N_k - \sigma_k - \sum_{\forall j \in W} (\delta_{fkj}\pi_{jk} + V_{fkj}N_k\rho_j)\end{aligned} \tag{4.20}$$

Our pricing problem is similar to the USS model, except for the modified objective function:

$$Min \quad \left(\sum_{\forall i} \sum_{\forall j} usage_i qty_i t_{ij} X_{ij} + \sum_{\forall j} invc_j Y_j \right) N_k - \sigma_k - \sum_{\forall j \in W} \left(V_k N_k \rho_j Y_j + \pi_{jk} Z_j \right) \quad (4.21)$$

By reordering the terms of the objective function, our pricing problem becomes:

$$Min \quad \sum_{\forall i} \sum_{\forall j} N_k usage_i qty_i t_{ij} X_{ij} + \sum_{\forall j \in W} \left(N_k invc_j - V_k N_k \rho_j \right) Y_j - \sum_{\forall j \in W} \pi_{jk} Z_j - \sigma_k \quad (4.22)$$

$$s.t. \quad Cover) \quad \sum_{\forall j} X_{ij} = 1 \qquad , \forall i \in Z \quad (4.23)$$

$$Sharing) \quad \sum_{\forall i} qty_i X_{ij} \le s Y_j \qquad , \forall j \in W \quad (4.24)$$

$$Forcing) \quad X_{ij} \le Y_j \qquad , \forall i \in Z, \forall j \in W \quad (4.25)$$

$$Forcing) \quad X_{ij} \le Z_j \qquad , \forall i \in Z, \forall j \in W \quad (4.26)$$

$$0 \le X_{ij} \le 1 \quad (4.27)$$

$$Y_j \ Integer \in [0, Mininv] \quad (4.28)$$

$$Z_j \ Binary \quad (4.29)$$

In the objective function (4.22), we minimize the transportation costs, inventory holding cost, and dual values from the master problem. The cover constraint (4.23) ensures that all demand in each customer region has been assigned to FSLs. Sharing constraint (4.24) ensures that parts are sufficiently stocked at each FSL to serve its assigned customer region, and that at least the minimum amount of inventory is stocked. Forcing constraint (4.25) serves to strengthen the LP bound. Forcing constraint (4.26) ensures that the FSL is open when any part is stocked there. Constraints (4.27) to (4.29) bind the range of values of the decision variables.

4.4.3.6.2 Branching Strategy

We use a straightforward branching strategy by branching on the decision variables for opening or closing the FSLs. The order of FSLs to branch on is determined by the decision variable with the value closest to one. A depth-first search is performed by working down the tree by opening successive FSLs. Then we backtrack up the tree in search for better solutions. Along the way, we prune sub-trees in a conventional branch-and-bound approach.

Chapter 5

5.0 Inventory Optimization

5.1 Overview

In this chapter, we present and analyze the results of our inventory optimization methodology. First, we seek to understand the inherent tradeoff between cost components as shown previously in Figure 4. The shape and position of the cost tradeoff curves also varies depending on the part's characteristics, such as cost, weight, and failure rate. Because capacity constraints introduce an additional level of complexity into our models, we first isolate the effect of part characteristics on distribution strategy in a capacity unconstrained model. This provides us with a basic understanding of how characteristics of a part affect its optimal distribution and stocking strategy. Then, we incorporate all parts in a capacity constrained model, which is an optimal inventory stocking tool applicable to the 3PL's inventory optimization process.

5.2 Single Generic SKU Unconstrained Scenarios

5.2.1 Overview

In this model, we optimize the distribution strategy for a single part without any capacity constraints. The goal is to understand how varying part characteristics affect the stocking solution. Specifically, the part characteristics studied are part cost, weight, and failure rate. The cost components are inventory holding, transportation, and warehouse storage.

The approach we use for our analysis is to enumerate combinations of part characteristics, generate a corresponding optimal solution, and analyze the results.

5.2.2 Part Characteristics Segmentation Scenarios

Instead of enumerating all parts, we focus on generating a few representative part scenarios from the data provided by the 3PL. We construct valid ranges along each dimension of part characteristics, namely part cost, part weight, and failure rate. The part scenarios are a complete enumeration of the combination of the following elements:

Part Characteristic	**Values**
Failure Rate (#/installation/yr)	0.00005, 0.0005, 0.001, 0.005, 0.01, 0.05, and 0.1
Cost ($)	10, 100, 500, 1000, 5000, and 10000
Weight (lbs)	1, 10, 50, 100, and 150

Table 2. Part Characteristics Values for Single Generic SKU Capacity Unconstrained Scenarios.

Each resulting combination is referred to as a generic SKU. A complete list of all 210 generic SKUs can be found in Appendix A1.

5.2.3 Model and Data Setup

We use the USS model with objective function (4.1) and constraints (4.2) to (4.6). For each generic SKU scenario, we define customer regions along 3-digit zip code boundaries and include 78 existing FSLs throughout the continental U.S.

5.2.4 Analysis

We provide the following data for each generic SKU scenario from our computational runs (see Appendix A1):

- Transportation cost;
- Inventory holding cost;
- Objective function;
- Best bound;
- Optimality gap;
- Solution run times;
- Inventory level; and
- Number of stocking locations.

Detailed stocking solutions are provided in Appendix A2. Both the inventory level and number of stocking locations are good indicators of the nature of the distribution strategy. For example, high inventory levels and numbers of stocking locations suggest a decentralized strategy. We measure the inventory level by summing the total safety stock held at all FSLs, and the degree of decentralization by counting the number of FSLs used. From the results, we draw the following key observations:

1) Certain FSLs are more logistically strategic.

From the stocking solution (Appendix A2), we observe that certain FSLs are selected as stocking points very frequently, while others are selected far fewer times. For example, Louisville (Kentucky) and Chester (Pennsylvania) are selected more than twenty times as often as the average of the remaining FSLs. Louisville is highly economical because of its central location and the economies of scale gained from its size. Chester is probably strategic because of its proximity to the major population hubs along the East coast.

The next tier of favorable locations are Santa Ana (California), Sacramento (California), Portland (Oregon), Dallas (Texas), Fort Lauderdale (Florida), and Arden Hills (Minnesota). They are each selected from four to ten times as often as the average of the remaining FSLs. Their locations along the periphery of the continent suggests their suitability as strategic locations in a decentralization strategy.

2) The impact of part cost and weight on inventory level and degree of decentralization is more pronounced with higher failure rates.

From the graphs in Appendices A3 and A4, we observe that the differences in inventory level and number of distinct stocking locations for varying part cost and weight scenarios increases, and becomes more disparate as the failure rate increases. This is because the number of parts shipped increases with the failure rate, and accentuates the impact of transportation and inventory holding cost on the distribution strategy. Thus, parts that have high failure rates deserve more attention as planning errors are likely to propagate into more pronounced negative cost and service consequences.

3) Inventory stock and decentralization degree increase with decreasing part cost.

The relationship is best represented by graphs, as seen in Figures 8 and 9. We refer readers to Appendices A3 and A4 for a complete set of graphs across all failure rates.

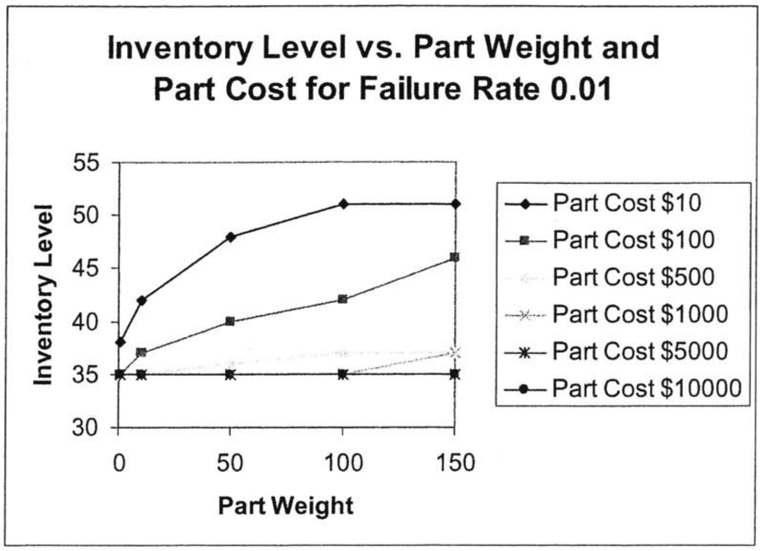

Figure 8. Inventory Level vs. Part Weight and Part Cost for Failure Rate 0.01.

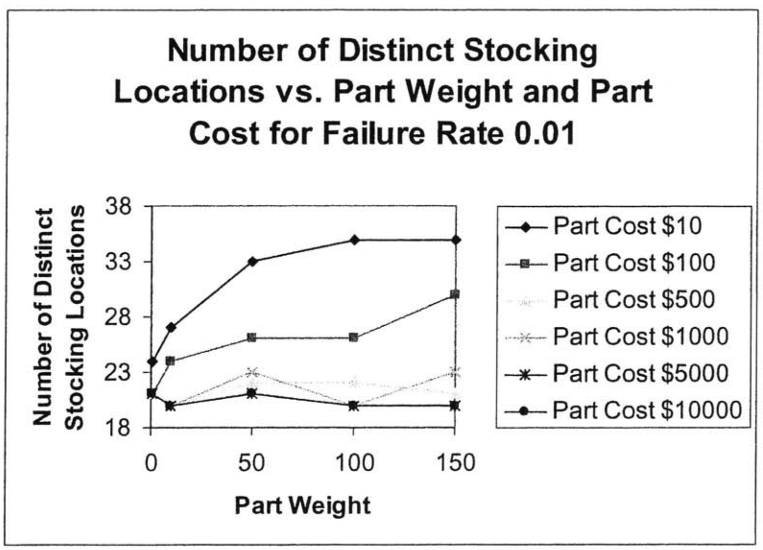

Figure 9. Number of Stocking Locations vs. Part Weight and Part Cost for Failure Rate 0.01.

We observe that for a given failure rate and part weight, the inventory level and number of stocking locations are higher for cheaper parts. This is because greater decentralization is economically advantageous – the increase in inventory investment is more than offset by a reduction in transportation costs.

4) Inventory stock and decentralization degree increase with increasing part weight. While an exhaustive set of graphs is available in Appendices A3 and A4, we refer readers to Figures 8 and 9 again as an example to highlight the relationship. As the part weight increases, it becomes more cost effective to stock parts closer to customers and use the cheaper ground replenishment modes. The cost discrepancy between air and ground shipment increases with the weight of the shipment. Thus, decentralization is favored for heavier parts.

We note, however, that there is a limit to this effect for higher failure rates. As seen in Figure 10, the number of stocking locations increases up to a certain point before decreasing for each curve. Although the reason is not very clear, we suspect that there is a saturation point for large safety stocks associated with the high failure rates, because there is always sufficient inventory to stock at various FSLs. Varying inventory holding cost at each FSL may play a bigger role in consolidating the inventory to a few key locations.

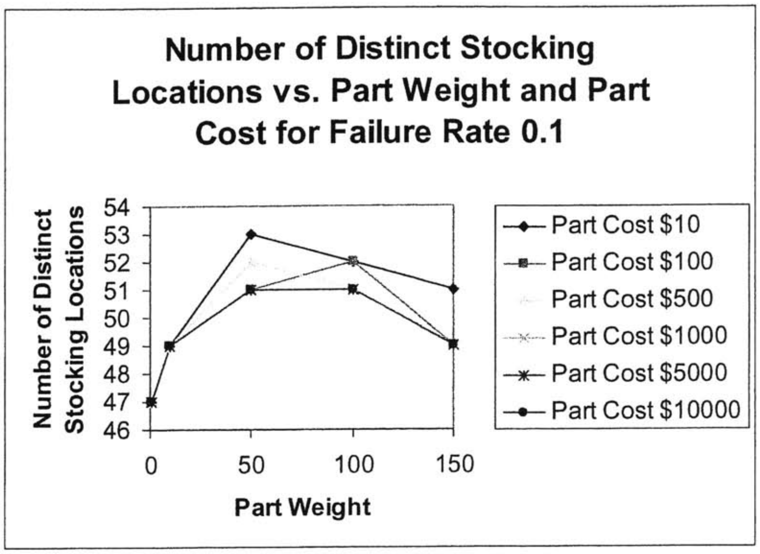

Figure 10. Number of Stocking Locations vs. Part Weight and Part Cost for Failure Rate 0.1.

5) Decentralization is highly favorable.

Referring to Appendix A4, we observe that centralization of all stock in one location is seldom a good distribution strategy, unless the demand rate is very low. Even for very expensive and light weight parts that discourage decentralization, a few stocking locations are usually selected. This suggests that decentralization should be imperative for SPP.

6) Solution run time depends on the transportation and inventory holding cost ratio.

We plotted the solution run time against the transportation and inventory holding cost ratio, as seen in Appendix A5. The run times are usually very short for scenarios where the transportation cost dominates the inventory holding cost, which applies to the less expensive part cost scenarios. On the other hand, when the ratio is small, run times can vary widely, but the longer run times tend to be associated with moderate part failure rates.

These observations provide us with a better understanding of the role of part characteristics on the distribution strategy without the complications of capacity constraints and fixed costs.

5.3 Multiple Generic SKUs Capacity Constrained Scenarios

5.3.1 Overview

Upon understanding the cost tradeoffs associated with varying part characteristics, we are better poised to implement and extract insights from a comprehensive inventory optimization model, which incorporates all parts in a capacity constrained network. The goal is to allocate the available FSL capacities to the parts at the lowest cost possible, while satisfying capacity constraints. This model, which is applicable to the 3PL's service parts planning operations, can be run regularly as new part data and forecasts are updated.

5.3.2 Model and Data Setup

We use the CFCM model consisting of the master problem with objective function (4.15) and constraints (4.16) to (4.19), and the pricing problem with objective function (4.22) and constraints (4.23) to (4.29).

Customer demand regions and FSLs are aggregated at the state level, providing sufficient detail and ensuring model tractability. There are no fixed costs associated with opening an FSL, so the parameter F_j is zero for all FSLs. Instead, we incorporate fixed cost into individual SKU inventory holding costs by charging a storage fee based on a percentage of the square footage leasing rate at each FSL (i.e., each SKU will incur a different inventory holding cost when stocked at different FSLs). Appendix B has tabulated and illustrated capacity and leasing rates for each FSL, providing us with a good overview of the FSL network and the spread of real estate rates across the continental U.S.

Because of time constraints and the exponential computational complexity involved when the number of parts modeled increases in the CFCM model, we limit our model to handle only 64 generic SKUs. We use sample data from the 3PL to generate reasonable ranges of part characteristics (see Table 2).

Part Characteristic	**Values**
Failure Rate (#/installation/yr)	0.0001, 0.001, 0.01, and 0.1
Cost ($)	10, 100, 500, and 1000
Weight (lbs)	1, 10, 50, and 150

Table 3. Part Characteristic Values for Multiple Generic SKU Capacity Constrained Scenarios.

A list of the generic SKU groups are provided in Appendix C1. The data was also used to derive the distributions of real parts fitting into each generic SKU category (see Appendix C2).

While we have the FSL storage capacities, the amount allocated to the overnight segment is unknown. Thus, we adopt a scenario analysis approach by proportionally varying the available capacity at each FSL, or equivalently the number of real parts. Thus, we simulate the environment where total volume is at 20%, 40%, 60%, and 80% of total capacity levels. This provides us with a good indication of the impact of growth in the overnight segment. We assume that each generic SKU has the same part dimensions to simplify our analysis and reduce the number of generic SKUs.

5.3.3 Analysis

We summarize the cost objective values, solution times, and stocking solutions for each volume level in Appendix C3. Illustrations of the stocking solutions for each volume level are in Appendices C4 to C7. Results show that the central warehouse at Kentucky gets the bulk of the inventory, and some of the periphery states like California, Texas, Virginia, Pennsylvania, Oregon, New York, North Carolina, Maryland, Massachusetts, Minnesota, Florida, and Georgia also show significant inventory with increasing volume levels. The states around Kentucky are the last to be filled with inventory because Kentucky serves as the most cost effective distribution location in that region. Thus, the former are filled up only when the capacity at Kentucky has been maxed out. The progression of periphery states being stocked with inventory shows that decentralization is necessary to achieve minimum cost. Even relatively more expensive stocking areas like New York, Minnesota, and Maryland are used to support the distribution strategy. It suggests that for some parts, transportation cost savings outweigh the higher storage costs at those expensive areas.

The total cost triples when volume increases from 20% to 40%, but grows at about 50% and 40% for the 40% to 60% and 60% to 80% increase respectively. This is because inventory gets stocked at less desirable locations when capacity at favorable locations depletes. This highlights the positive impact of building up capacity at the right locations to accommodate volume growth. The distribution strategy is highly dependent on the FSL network, and significantly affects the bottom line.

Run times almost double for every 20% increase in volume, which demonstrates the exponential surge in planning complexity with the increasing number of real parts.

Chapter 6

6.0 Facility Network Design

6.1 Overview

In the previous chapter, we have optimized the inventory plan by treating the facility network as fixed. In this chapter, we allow flexibility in designing the facility network to best support the operating strategy of the overnight segment. Although there are many other qualitative factors involved in locating FSLs, we adopt a cost minimizing approach. As explained earlier, operating margins in the overnight segment are lower; hence, a cost leadership approach is most appropriate. The facility network affects operating costs and the ability to achieve service performance targets efficiently. While traditionally deemed to be long term investments, leases allow greater flexibility in network designs. The key is to leverage the company's ability to change its network rapidly according to market conditions, such that its operations can run efficiently and at high service levels.

We approach facility network design by first running an unconstrained plan, whereby there are no capacity constraints and fixed costs tied to opening an FSL. This should provide us with insights on the ideal network design that minimizes operating costs. Then, we incorporate fixed costs and capacity constraints into our analysis. We first investigate the impact on individual SKUs of varying part characteristics, then for all SKUs simultaneously.

6.2 Unconstrained Plan

6.2.1 Overview

The unconstrained plan consists essentially of executing the USS model for every SKU, and aggregating the volume requirements at each FSL. It determines the solution and delta between the ideal network design and the current network, if we ignore real estate and FSL infrastructure costs. The unconstrained plan could be applicable when service is of utmost importance. For example, emergency services such as fire departments, which have to be located within a certain maximum distance from the neighborhood, and real estate and infrastructure costs are of relatively much lower importance. Although not very applicable to the service parts industry, even for the two hour responses, the unconstrained plan is useful for extracting insights on the impact of fixed costs and capacity constraints.

6.2.2 Model and Data Setup

We execute the CFCM model consisting of the master problem with objective function (4.15) and constraints (4.16) to (4.19), and the pricing problem with objective function (4.22) and constraints (4.23) to (4.29), for each of the 64 generic SKUs in Appendix C1. For each FSL, fixed cost is zero and capacity is infinite. The number of real parts fitting in each generic SKU group is the same as the multiple SKU inventory optimization scenario discussed in chapter 5 (see Appendix C2). The inventory holding cost incurred for stocking a part is uniform across all FSLs. We vary the total volume of parts from 20% to 100% of total capacity to observe how the distribution strategy evolves to accommodate more volume.

6.2.3 Analysis

We summarize the cost objective values, solution times, and stocking solutions for each volume level in Appendix D1. Illustrations of the stocking solutions for each volume level can be found in Appendices D2 to D6. As seen in the maps, the central (Kentucky) and periphery states (California, Texas, Oregon, Delaware, Florida, and New York) get significantly more volume than the other regions. This can be attributed to the lower distribution costs of serving the central regions from Louisville, and the other states from the periphery states selected in the solution.

There is not much difference between the stocking solution obtained and that of the inventory optimization discussed in the previous chapter, except for some states, which are heavily overloaded (e.g., Delaware, New Hampshire, and Wyoming). This suggests that if the capacity at these locations could be procured at reasonably cheap rates, then they could potentially add value to the FSL network. Unfortunately, there might be qualitative factors that make such investments prohibitive, for example, whether the quality and reliability of overnight delivery are sufficient.

6.3 Capacitated Fixed Charge Scenarios

6.3.1 Overview

In this step, we design the network from scratch by opening FSLs that simultaneously minimize both facility network costs (fixed cost) at the FSL level and distribution costs (transportation and inventory holding) at the SKU level, subject to capacity constraints. Similar to the inventory optimization approach, we proceed by analyzing from the SKU level initially, before combining all SKUs into one model. The key tradeoff in these facility network designs is that of fixed costs and distribution costs. Unless there is very strong incentive to decentralize due to part characteristics, the fixed cost element can easily dominate the distribution costs and favor a centralized strategy.

6.3.2 Model and Data Setup

We use the CFCM model consisting of the master problem with objective function (4.15) and constraints (4.16) to (4.19), and the pricing problem with objective function (4.22) and constraints (4.23) to (4.29). The choices of FSLs to open are the existing FSLs in the 3PL's network, because of the availability of capacity and fixed cost data provided for these FSLs. Although the selection of the existing FSLs is clearly not extensive, we do not have data for a list of potential FSLs. Nevertheless, the existing FSLs are widely scattered around the continental U.S., and capture the real estate economics of the various locations. Furthermore, aggregation at the state level nullifies the necessity to define potential sites at the detailed city level.

6.3.3 Single Generic SKU Analysis

Appendices E1, E2, and E3 contain the results of the analysis in terms of objective values, run times, and state tally respectively. The state tally is an illustration of the number of times the solution picked a particular state to setup an FSL. The solution often contains the same set of facilities across the generic SKU categories. They always included Louisville because of its low cost and central geographic position. When volume is low, the other FSLs selected were in central locations with low capacity and low rental rates. This suggests that decentralization is not the main motivation. Even for high volume scenarios, the solution always avoids the expensive FSLs. However, a high capacity, moderately expensive facility might be picked to serve a region, rather than a few scattered FSLs with low cost. As we increase demand volume, the generic SKUs having centralized stocking solutions tend to have its cost increase the most.

Because of the network design nature of the model where a facility is either open or closed, we observe that decisions tend to exhibit stepped behavior. FSLs selected are used completely up to capacity before investing in additional facilities. Thus, there are strong incentives to setup the FSLs in cheaper regions. Real estate economics seem to be driving most of the network decisions, more so than the transportation and inventory cost tradeoffs. It dictates that cheaper regions should be established first to accommodate demand. Although we would expect decentralization in certain categories of generic SKUs, they were evident only in the SKUs with heavy weight, low cost, and high failure rate. These parts had optimal networks consisting of periphery states.

6.3.4 Multiple Generic SKUs Analysis

We summarize the cost objective values, solution times, optimality gaps, and stocking solutions for each volume level in Appendix F1. Illustrations of the stocking solutions for each volume level are in Appendices F2 to F5. The resulting distribution strategy is highly centralized with FSLs setup in inexpensive areas. Thus, the decentralization incentives are outweighed by the fixed cost associated with opening subsequent FSLs. This network optimization approach is not particularly relevant to the 3PL because they already have a network in place, and the goal is to tap into available FSL capacities across the nation to save on distribution costs. Nonetheless, it provides validation of the dominant effect of real estate economics when we consider fixed costs in an all-or-none situation. In the next section, we discuss a hybrid model that takes into account the existing FSL network and potential FSLs.

6.4 Hybrid Model Discussion

We incorporate the existing FSL network and potential opportunities in the modified restricted master problem:

$$\text{Minimize} \quad \sum_{\forall f}\sum_{\forall k} C_{fk} N_k G_{fk} + \sum_{\forall j} F_j Z_j \tag{4.30}$$

$$s.t. \quad \text{Convexity)} \quad \sum_{\forall f} G_{fk} = 1 \qquad ,\forall k \in P \tag{4.31}$$

$$\text{Forcing)} \quad \sum_{\forall f} \delta_{fkj} G_{fk} \le Z_j \qquad ,\forall j \in W, \forall k \in P \tag{4.32}$$

$$\text{Capacity)} \quad \sum_{\forall k}\sum_{\forall f} V_{fkj} G_{fk} N_k \le Cap_j + Newcap_j Z_j \qquad ,\forall j \in W \tag{4.33}$$

$$\text{Upperbound)} \quad Z_j \le 1 \qquad ,\forall j \in W \tag{4.34}$$

$$\text{Lowerbound)} \quad Z_j \ge 0 \qquad ,\forall j \in W \tag{4.35}$$

$Newcap_j$ is the additional expansion capacity available at FSL region j, F_j is the fixed cost of procuring that additional capacity, and Z_j is the decision variable of whether to procure the additional capacity. The pricing problem remains unchanged as in (4.22) to (4.29).

The hybrid model is a blend of the inventory optimization and network design modules. We optimize the inventory stocking plan within the capacity limits of the current FSL network, and yet allow freedom to procure additional blocks of capacity at certain fixed costs. This is especially applicable to the 3PL because it requires the existing network to support the quicker response two-hour services, which the overnight segment can also utilize. In addition, capacity can be procured to improve the overnight delivery operations.

Chapter 7

7.0 Conclusions and Future Research

7.1 Conclusions

In this paper, we have introduced the operating environment and challenges of the service parts business. The high uncertainty intrinsic to service parts and large scale operations, in millions of SKUs, of a 3PL pose particularly problematical obstacles to overcome. By focusing on the overnight delivery segment, separating certain inventory stocking decisions, aggregating data along generic parts and geographical regions, and using large scale operations research techniques, we have managed to formulate two deterministic models that are very scalable and tractable.

The first model is the Uncapacitated Single SKU (USS) that determines the optimal inventory stocking plan for a single part based on minimizing cost parameters and fulfilling service constraints. By analyzing the distribution strategy for parts of varying characteristics, we found that decentralization is still strongly favored at a few logistically strategic locations, but the degree of decentralization increases with cheaper and heavier parts, and the effect made more pronounced with parts of higher failure rates.

The USS model is a building block for the Capacitated Fixed Charge Multi-SKU (CFCM) model, which incorporates warehouse capacity and fixed costs, and optimizes across multiple parts. Using data from a 3PL, we showed that the model could generate optimal inventory stocking plans for all parts quickly, and the solution of a large central warehouse and moderately sized warehouses in the periphery states of the continent was in line with our expectations. When we included fixed warehouse costs, however, we discovered that the fixed costs were significantly greater than the cost savings gained from decentralization; hence, the optimal network structure was highly centralized. This highlighted a shortcoming in our model in that the more restrictive network structure demanded for the quicker responses (e.g., 2 and 4hr services) should be factored. We have suggested a hybrid model to work around this deficiency, in which the existing network and potential incremental capacity investments are modeled. Nevertheless, we have extracted valuable insights into the tradeoffs of part characteristics, impact of real estate economics, and effective large-scale solution techniques for SPP. The inventory optimization methods discussed will be most applicable and useful for the 3PL.

7.2 Future Research

We have so far restricted our study to the overnight delivery segment; hence, more holistic approaches can be studied, whereby all response time segments (e.g., 2hr, 4hr, same day, and overnight) offered by the 3PL are incorporated into a single model to achieve global optimum. The CFCM framework can be used, where the master problem links all parts together in a capacity constrained and fixed cost model, and the pricing problem models individual part stocking strategies. More research into methods of incorporating the stochastic elements of risk pooling, however, will be most imperative for an effective model.

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Appendix A1. Generic SKU Scenarios.

Population 248709873

Index	Installation %Population	# Installations	Failure Rate	Expected # Failures (annual)	Supplier Leadtime (days)	Minimum Inventory (CW)	Sharing Factor	Part Cost	% Inventory Holding (base)	% Inventory Holding (storage)	Part Weight (lbs)	tcost	invcost	tcost / invcost ratio	Best Solution	Best Bound	Optimality Gap	Solution Runtime (secs)	Solution Status*	Inventory Level	Distinct Stocking Locations
1	0.0001	24871	0.00005	1.24355	30	2	12435.50	10	30%	50%	1	24.75088	8	3.093859	32.750875	32.750875	0.000%	7	101	2	1
2	0.0001	24871	0.00005	1.24355	30	2	12435.50	10	30%	50%	10	45.98465	8.98	5.120784	54.964645	54.964645	0.000%	165	101	2	2
3	0.0001	24871	0.00005	1.24355	30	2	12435.50	10	30%	50%	50	107.7177	19.22	5.604459	126.937704	126.937704	0.000%	329	101	4	4
4	0.0001	24871	0.00005	1.24355	30	2	12435.50	10	30%	50%	100	230.7435	19.22	12.00539	249.963509	249.585125	0.151%	83	102	4	4
5	0.0001	24871	0.00005	1.24355	30	2	12435.50	10	30%	50%	150	332.76	24.32	13.68257	357.079973	357.079973	0.000%	6	101	5	5
6	0.0001	24871	0.00005	1.24355	30	2	12435.50	100	30%	50%	1	24.75088	62	0.399208	86.750875	86.750875	0.000%	7	101	2	1
7	0.0001	24871	0.00005	1.24355	30	2	12435.50	100	30%	50%	10	45.98465	62.98	0.730147	108.964645	108.964645	0.000%	165	101	2	2
8	0.0001	24871	0.00005	1.24355	30	2	12435.50	100	30%	50%	50	119.1953	62.98	1.89259	182.175321	182.175321	0.000%	159	101	2	2
9	0.0001	24871	0.00005	1.24355	30	2	12435.50	100	30%	50%	100	256.9751	62	4.14476	318.975137	318.975137	0.000%	384	101	2	1
10	0.0001	24871	0.00005	1.24355	30	2	12435.50	100	30%	50%	150	378.7312	62.98	6.013516	441.711236	441.711236	0.000%	668	101	2	2
11	0.0001	24871	0.00005	1.24355	30	2	12435.50	500	30%	50%	1	24.75088	302	0.081957	326.750875	326.750875	0.000%	7	101	2	1
12	0.0001	24871	0.00005	1.24355	30	2	12435.50	500	30%	50%	10	45.98465	302.98	0.151775	348.964645	348.964645	0.000%	167	101	2	2
13	0.0001	24871	0.00005	1.24355	30	2	12435.50	500	30%	50%	50	119.1953	302.98	0.39341	422.175322	422.175322	0.000%	159	101	2	2
14	0.0001	24871	0.00005	1.24355	30	2	12435.50	500	30%	50%	100	256.9751	302	0.850911	558.975138	558.975138	0.000%	384	101	2	1
15	0.0001	24871	0.00005	1.24355	30	2	12435.50	500	30%	50%	150	378.7312	302.98	1.250021	681.711236	681.711236	0.000%	435	101	2	2
16	0.0001	24871	0.00005	1.24355	30	2	12435.50	1000	30%	50%	1	24.75088	602	0.041114	626.750875	626.750875	0.000%	7	101	2	1
17	0.0001	24871	0.00005	1.24355	30	2	12435.50	1000	30%	50%	10	45.98465	602.98	0.076262	648.964645	648.964645	0.000%	165	101	2	2
18	0.0001	24871	0.00005	1.24355	30	2	12435.50	1000	30%	50%	50	119.1953	602.98	0.197677	722.175322	722.175322	0.000%	159	101	2	2
19	0.0001	24871	0.00005	1.24355	30	2	12435.50	1000	30%	50%	100	256.9751	602	0.426869	858.975138	858.975138	0.000%	384	101	2	1
20	0.0001	24871	0.00005	1.24355	30	2	12435.50	1000	30%	50%	150	378.7312	602.98	0.628099	981.711236	981.711236	0.000%	434	101	2	2
21	0.0001	24871	0.00005	1.24355	30	2	12435.50	5000	30%	50%	1	24.75088	3002	0.008245	3026.750875	3026.75088	0.000%	6	101	2	1
22	0.0001	24871	0.00005	1.24355	30	2	12435.50	5000	30%	50%	10	45.98465	3002.98	0.015313	3048.964645	3048.96465	0.000%	165	101	2	2
23	0.0001	24871	0.00005	1.24355	30	2	12435.50	5000	30%	50%	50	119.1953	3002.98	0.039692	3122.175321	3122.17532	0.000%	159	101	2	2
24	0.0001	24871	0.00005	1.24355	30	2	12435.50	5000	30%	50%	100	256.9751	3002	0.085601	3258.975137	3258.97514	0.000%	384	101	2	1
25	0.0001	24871	0.00005	1.24355	30	2	12435.50	5000	30%	50%	150	378.7312	3002.98	0.126118	3381.711237	3381.71124	0.000%	434	101	2	2
26	0.0001	24871	0.00005	1.24355	30	2	12435.50	10000	30%	50%	1	24.75088	6002	0.004124	6026.750875	6026.75088	0.000%	7	101	2	1
27	0.0001	24871	0.00005	1.24355	30	2	12435.50	10000	30%	50%	10	45.98465	6002.98	0.00766	6048.964645	6048.96465	0.000%	165	101	2	2
28	0.0001	24871	0.00005	1.24355	30	2	12435.50	10000	30%	50%	50	119.1953	6002.98	0.019856	6122.175321	6122.17532	0.000%	158	101	2	2
29	0.0001	24871	0.00005	1.24355	30	2	12435.50	10000	30%	50%	100	256.9751	6002	0.042815	6258.975137	6258.97514	0.000%	384	101	2	1
30	0.0001	24871	0.00005	1.24355	30	2	12435.50	10000	30%	50%	150	378.7312	6002.98	0.063091	6381.711236	6381.71124	0.000%	434	101	2	2
31	0.0001	24871	0.0005	12.4355	30	5	4974.20	10	30%	50%	1	237.8913	22.34	10.64867	260.23132	260.099916	0.051%	107	102	5	3
32	0.0001	24871	0.0005	12.4355	30	5	4974.20	10	30%	50%	10	376.2973	52.78	7.129543	429.077283	427.193464	0.439%	229	102	10	10
33	0.0001	24871	0.0005	12.4355	30	5	4974.20	10	30%	50%	50	906.7875	82.17	11.03551	988.957451	987.412142	0.156%	21	102	15	15
34	0.0001	24871	0.0005	12.4355	30	5	4974.20	10	30%	50%	100	2026.247	109.96	18.42713	2136.207189	2133.21201	0.140%	13	102	20	20
35	0.0001	24871	0.0005	12.4355	30	5	4974.20	10	30%	50%	150	2935.161	121.32	24.19355	3056.480984	3054.47966	0.066%	21	102	22	22
36	0.0001	24871	0.0005	12.4355	30	5	4974.20	100	30%	50%	1	237.8913	157.34	1.511957	395.23132	395.23132	0.000%	67	101	5	3
37	0.0001	24871	0.0005	12.4355	30	5	4974.20	100	30%	50%	10	422.9623	159.46	2.652466	582.422255	579.875325	0.437%	1608	102	5	5
38	0.0001	24871	0.0005	12.4355	30	5	4974.20	100	30%	50%	50	1009.634	234.97	4.296866	1244.604494	1238.84635	0.463%	605	102	7	7
39	0.0001	24871	0.0005	12.4355	30	5	4974.20	100	30%	50%	100	2182.223	291.04	7.498017	2473.262909	2466.20129	0.286%	56	102	9	8
40	0.0001	24871	0.0005	12.4355	30	5	4974.20	100	30%	50%	150	3146.527	326.13	9.648077	3472.657216	3465.88073	0.195%	138	102	10	9
41	0.0001	24871	0.0005	12.4355	30	5	4974.20	500	30%	50%	1	237.8913	757.34	0.314114	995.23132	995.23132	0.000%	67	101	5	3
42	0.0001	24871	0.0005	12.4355	30	5	4974.20	500	30%	50%	10	422.9623	759.46	0.556925	1182.422255	1178.63749	0.320%	1189	102	5	5
43	0.0001	24871	0.0005	12.4355	30	5	4974.20	500	30%	50%	50	1105.561	759.73	1.455202	1865.290808	1855.3729	0.532%	3724	107	5	5
44	0.0001	24871	0.0005	12.4355	30	5	4974.20	500	30%	50%	100	2363.346	764.88	3.089826	3128.226029	3117.48322	0.343%	68	102	5	3
45	0.0001	24871	0.0005	12.4355	30	5	4974.20	500	30%	50%	150	3475.117	764.88	4.543349	4239.996813	4227.06656	0.305%	157	102	5	3
46	0.0001	24871	0.0005	12.4355	30	5	4974.20	1000	30%	50%	1	237.8913	1507.34	0.157822	1745.23132	1745.23132	0.000%	67	101	5	3
47	0.0001	24871	0.0005	12.4355	30	5	4974.20	1000	30%	50%	10	422.9623	1509.46	0.280208	1932.422255	1928.63749	0.196%	1183	102	5	5
48	0.0001	24871	0.0005	12.4355	30	5	4974.20	1000	30%	50%	50	1105.561	1509.73	0.73229	2615.290808	2603.15749	0.464%	3256	102	5	5
49	0.0001	24871	0.0005	12.4355	30	5	4974.20	1000	30%	50%	100	2363.346	1514.88	1.560088	3878.226029	3867.48322	0.277%	69	102	5	3
50	0.0001	24871	0.0005	12.4355	30	5	4974.20	1000	30%	50%	150	3475.117	1514.88	2.293988	4989.996813	4977.06656	0.259%	91	102	5	3
51	0.0001	24871	0.0005	12.4355	30	5	4974.20	5000	30%	50%	1	237.8913	7507.34	0.031688	7745.23132	7745.23132	0.000%	67	101	5	3
52	0.0001	24871	0.0005	12.4355	30	5	4974.20	5000	30%	50%	10	422.9623	7509.46	0.056324	7932.422255	7928.63749	0.048%	1184	102	5	5
53	0.0001	24871	0.0005	12.4355	30	5	4974.20	5000	30%	50%	50	1105.561	7509.73	0.147217	8615.290808	8601.08748	0.165%	2556	102	5	5
54	0.0001	24871	0.0005	12.4355	30	5	4974.20	5000	30%	50%	100	2363.346	7514.88	0.314489	9878.226029	9867.48322	0.109%	68	102	5	3
55	0.0001	24871	0.0005	12.4355	30	5	4974.20	5000	30%	50%	150	3475.117	7514.88	0.462431	10989.99681	10977.0666	0.118%	91	102	5	3
56	0.0001	24871	0.0005	12.4355	30	5	4974.20	10000	30%	50%	1	237.8913	15007.34	0.015852	15245.23132	15245.2313	0.000%	67	101	5	3
57	0.0001	24871	0.0005	12.4355	30	5	4974.20	10000	30%	50%	10	422.9623	15009.46	0.02818	15432.42226	15428.6375	0.025%	1181	102	5	5
58	0.0001	24871	0.0005	12.4355	30	5	4974.20	10000	30%	50%	50	1105.561	15009.73	0.073656	16115.29081	16101.0875	0.088%	2558	102	5	5
59	0.0001	24871	0.0005	12.4355	30	5	4974.20	10000	30%	50%	100	2363.346	15014.88	0.1574	17378.22603	17367.4832	0.062%	68	102	5	3
60	0.0001	24871	0.0005	12.4355	30	5	4974.20	10000	30%	50%	150	3475.117	15014.88	0.231445	18489.99681	18475.2262	0.080%	94	102	5	3
61	0.0001	24871	0.001	24.871	30	7	3553.00	10	30%	50%	1	468.6635	37.1	12.63244	505.763473	504.072824	0.334%	148	102	8	5
62	0.0001	24871	0.001	24.871	30	7	3553.00	10	30%	50%	10	723.1985	75.64	9.561059	798.838509	795.111089	0.467%	51	102	14	13

63	0.0001	24871	0.001	24.871	30	7	3553.00	10	30%	50%	50	1793.757	108.87	16.47613	1902.626697	1894.72919	0.415%	38	102	20	19
64	0.0001	24871	0.001	24.871	30	7	3553.00	10	30%	50%	100	4030.624	140.17	28.75525	4170.79394	4152.35846	0.442%	14	102	25	24
65	0.0001	24871	0.001	24.871	30	7	3553.00	10	30%	50%	150	5864.423	142.67	41.10481	6007.09327	5982.28776	0.413%	15	102	26	25
66	0.0001	24871	0.001	24.871	30	7	3553.00	100	30%	50%	1	475.1619	219.34	2.166326	694.50185	693.43339	0.154%	53	102	7	3
67	0.0001	24871	0.001	24.871	30	7	3553.00	100	30%	50%	10	805.3233	225.5	3.571279	1030.823319	1026.42039	0.427%	436	102	7	6
68	0.0001	24871	0.001	24.871	30	7	3553.00	100	30%	50%	50	1905.872	359.44	5.302336	2265.311731	2254.49601	0.477%	383	102	11	11
69	0.0001	24871	0.001	24.871	30	7	3553.00	100	30%	50%	100	4176.968	461.13	9.058115	4638.09835	4619.88956	0.393%	23	102	14	12
70	0.0001	24871	0.001	24.871	30	7	3553.00	100	30%	50%	150	6058.856	493.19	12.28503	6552.04589	6543.15117	0.136%	25	102	15	13
71	0.0001	24871	0.001	24.871	30	7	3553.00	500	30%	50%	1	475.1619	1059.34	0.448545	1534.50185	1533.43339	0.070%	53	102	7	3
72	0.0001	24871	0.001	24.871	30	7	3553.00	500	30%	50%	10	805.3233	1065.5	0.755817	1870.823319	1866.42039	0.235%	435	102	7	6
73	0.0001	24871	0.001	24.871	30	7	3553.00	500	30%	50%	50	2051.456	1074.97	1.908385	3126.42613	3126.08581	0.011%	490	102	7	7
74	0.0001	24871	0.001	24.871	30	7	3553.00	500	30%	50%	100	4629.552	1069.84	4.327331	5699.392216	5683.35121	0.282%	628	102	7	5
75	0.0001	24871	0.001	24.871	30	7	3553.00	500	30%	50%	150	6600.102	1224.04	5.392064	7824.141523	7807.29682	0.215%	115	102	8	6
76	0.0001	24871	0.001	24.871	30	7	3553.00	1000	30%	50%	1	475.1619	2109.34	0.225266	2584.50185	2583.43339	0.041%	53	102	7	3
77	0.0001	24871	0.001	24.871	30	7	3553.00	1000	30%	50%	10	805.3233	2115.5	0.380678	2920.823319	2916.42039	0.151%	435	102	7	6
78	0.0001	24871	0.001	24.871	30	7	3553.00	1000	30%	50%	50	2051.456	2124.97	0.965405	4176.42613	4176.08581	0.008%	492	102	7	7
79	0.0001	24871	0.001	24.871	30	7	3553.00	1000	30%	50%	100	4629.552	2119.84	2.183916	6749.392216	6719.59032	0.442%	502	102	7	5
80	0.0001	24871	0.001	24.871	30	7	3553.00	1000	30%	50%	150	6781.655	2123.04	3.194313	8904.694681	8877.60644	0.304%	842	102	7	6
81	0.0001	24871	0.001	24.871	30	7	3553.00	5000	30%	50%	1	475.1619	10509.34	0.045213	10984.50185	10983.4334	0.010%	53	102	7	3
82	0.0001	24871	0.001	24.871	30	7	3553.00	5000	30%	50%	10	805.3233	10515.5	0.076584	11320.82332	11316.4204	0.039%	437	102	7	6
83	0.0001	24871	0.001	24.871	30	7	3553.00	5000	30%	50%	50	2051.456	10524.97	0.194913	12576.42613	12576.0858	0.003%	490	102	7	7
84	0.0001	24871	0.001	24.871	30	7	3553.00	5000	30%	50%	100	4629.552	10519.84	0.440078	15149.39222	15115.5229	0.224%	323	102	7	5
85	0.0001	24871	0.001	24.871	30	7	3553.00	5000	30%	50%	150	6781.655	10523.04	0.644458	17304.69468	17247.4925	0.331%	448	102	7	6
86	0.0001	24871	0.001	24.871	30	7	3553.00	10000	30%	50%	1	475.1619	21009.34	0.022617	21484.50185	21483.4334	0.005%	53	102	7	3
87	0.0001	24871	0.001	24.871	30	7	3553.00	10000	30%	50%	10	805.3233	21015.5	0.03832	21820.82332	21816.4204	0.020%	436	102	7	6
88	0.0001	24871	0.001	24.871	30	7	3553.00	10000	30%	50%	50	2051.456	21024.97	0.097572	23076.42613	23076.0858	0.002%	491	102	7	7
89	0.0001	24871	0.001	24.871	30	7	3553.00	10000	30%	50%	100	4629.552	21019.84	0.220247	25649.39222	25615.5229	0.132%	324	102	7	5
90	0.0001	24871	0.001	24.871	30	7	3553.00	10000	30%	50%	150	6781.655	21023.04	0.322582	27804.69468	27747.4925	0.206%	448	102	7	6
91	0.0001	24871	0.005	124.355	30	20	1243.55	10	30%	50%	1	2232.323	134.59	16.5861	2366.913057	2362.44445	0.189%	53	102	26	19
92	0.0001	24871	0.005	124.355	30	20	1243.55	10	30%	50%	10	3484.349	148.61	23.44626	3632.95925	3629.65102	0.091%	53	102	28	21
93	0.0001	24871	0.005	124.355	30	20	1243.55	10	30%	50%	50	8807.505	181.24	48.59581	8988.7446	8986.89527	0.021%	15	102	33	26
94	0.0001	24871	0.005	124.355	30	20	1243.55	10	30%	50%	100	20019.55	233.16	85.86184	20252.70754	20174.427	0.387%	26	102	40	34
95	0.0001	24871	0.005	124.355	30	20	1243.55	10	30%	50%	150	29087.23	232.12	125.3112	29319.34541	29249.4594	0.238%	23	102	40	33
96	0.0001	24871	0.005	124.355	30	20	1243.55	100	30%	50%	1	2282.133	640.49	3.563104	2922.622608	2914.8452	0.266%	1957	102	20	13
97	0.0001	24871	0.005	124.355	30	20	1243.55	100	30%	50%	10	3581.465	684.67	5.230936	4266.134935	4246.93939	0.450%	1399	102	21	16
98	0.0001	24871	0.005	124.355	30	20	1243.55	100	30%	50%	50	8908.887	824.76	10.80179	9733.647482	9702.66502	0.318%	140	102	25	20
99	0.0001	24871	0.005	124.355	30	20	1243.55	100	30%	50%	100	20142.62	984.64	20.45684	21127.2637	21029.0864	0.465%	39	102	30	23
100	0.0001	24871	0.005	124.355	30	20	1243.55	100	30%	50%	150	29201.71	1078.7	27.0712	30280.40816	30162.5413	0.389%	34	102	33	26
101	0.0001	24871	0.005	124.355	30	20	1243.55	500	30%	50%	1	2279.474	3043.16	0.749048	5322.633972	5314.84039	0.146%	1068	102	20	13
102	0.0001	24871	0.005	124.355	30	20	1243.55	500	30%	50%	10	3636.519	3051.75	1.191618	6688.269295	6662.26474	0.389%	2797	102	20	16
103	0.0001	24871	0.005	124.355	30	20	1243.55	500	30%	50%	50	9133.895	3219.28	2.837248	12353.17533	12288.8286	0.521%	3733	107	21	17
104	0.0001	24871	0.005	124.355	30	20	1243.55	500	30%	50%	100	20801.76	3223.85	6.452458	24025.60772	23907.3124	0.492%	1187	102	21	15
105	0.0001	24871	0.005	124.355	30	20	1243.55	500	30%	50%	150	29750.51	3683.57	8.076541	33434.07582	33277.8521	0.467%	184	102	24	19
106	0.0001	24871	0.005	124.355	30	20	1243.55	1000	30%	50%	1	2279.474	6043.16	0.377199	8322.633973	8314.84039	0.094%	1108	102	20	13
107	0.0001	24871	0.005	124.355	30	20	1243.55	1000	30%	50%	10	3650.746	6047.84	0.603645	9698.585878	9655.91801	0.440%	1240	102	20	15
108	0.0001	24871	0.005	124.355	30	20	1243.55	1000	30%	50%	50	9347.078	6058.58	1.542784	15405.65833	15272.3411	0.865%	3718	107	20	15
109	0.0001	24871	0.005	124.355	30	20	1243.55	1000	30%	50%	100	20877.18	6367.65	3.278632	27244.83019	26951.4454	1.077%	3717	107	21	16
110	0.0001	24871	0.005	124.355	30	20	1243.55	1000	30%	50%	150	30283.59	6372.73	4.75206	36656.32406	36479.6378	0.482%	1621	102	21	15
111	0.0001	24871	0.005	124.355	30	20	1243.55	5000	30%	50%	1	2279.474	30043.16	0.075873	32322.63397	32314.8452	0.024%	1063	102	20	13
112	0.0001	24871	0.005	124.355	30	20	1243.55	5000	30%	50%	10	3650.746	30047.84	0.121498	33698.58588	33655.918	0.127%	1222	102	20	15
113	0.0001	24871	0.005	124.355	30	20	1243.55	5000	30%	50%	50	9347.078	30058.58	0.310962	39405.65833	39263.0893	0.362%	1500	102	20	15
114	0.0001	24871	0.005	124.355	30	20	1243.55	5000	30%	50%	100	21118.15	30063.45	0.702453	51181.60294	50941.7834	0.469%	1389	102	20	15
115	0.0001	24871	0.005	124.355	30	20	1243.55	5000	30%	50%	150	30676.89	30061.56	1.020469	60738.45463	60546.7932	0.316%	2681	102	20	14
116	0.0001	24871	0.005	124.355	30	20	1243.55	10000	30%	50%	1	2279.474	60043.16	0.037964	62322.63397	62314.8754	0.012%	910	102	20	13
117	0.0001	24871	0.005	124.355	30	20	1243.55	10000	30%	50%	10	3650.746	60047.84	0.060797	63698.58588	63655.918	0.067%	1191	102	20	15
118	0.0001	24871	0.005	124.355	30	20	1243.55	10000	30%	50%	50	9347.078	60058.58	0.155633	69405.65833	69263.0893	0.205%	1498	102	20	15
119	0.0001	24871	0.005	124.355	30	20	1243.55	10000	30%	50%	100	21118.15	60063.45	0.351597	81181.60294	80941.7834	0.295%	1529	102	20	15
120	0.0001	24871	0.005	124.355	30	20	1243.55	10000	30%	50%	150	30797.81	60063.45	0.512755	90861.26221	90504.3335	0.393%	1685	102	20	15
121	0.0001	24871	0.01	248.71	30	35	710.60	10	30%	50%	1	4445.893	195.95	22.68892	4641.842897	4629.42704	0.268%	192	102	38	24
122	0.0001	24871	0.01	248.71	30	35	710.60	10	30%	50%	10	6922.356	229.47	30.16671	7151.825811	7143.52323	0.116%	63	102	42	27
123	0.0001	24871	0.01	248.71	30	35	710.60	10	30%	50%	50	17559.68	271.68	64.63367	17831.35573	17816.1088	0.086%	21	102	48	33
124	0.0001	24871	0.01	248.71	30	35	710.60	10	30%	50%	100	39894.61	291.02	137.0855	40185.63261	40160.2741	0.063%	26	102	51	35
125	0.0001	24871	0.01	248.71	30	35	710.60	10	30%	50%	150	58027.41	285.43	203.2982	58312.8356	58302.5091	0.018%	16	102	51	35
126	0.0001	24871	0.01	248.71	30	35	710.60	100	30%	50%	1	4482.321	1124.47	3.986163	5606.790706	5584.04499	0.406%	826	102	35	21
127	0.0001	24871	0.01	248.71	30	35	710.60	100	30%	50%	10	6991.271	1201.83	5.817188	8193.100549	8153.98691	0.477%	1673	102	37	24
128	0.0001	24871	0.01	248.71	30	35	710.60	100	30%	50%	50	17651.38	1297.16	13.60771	18948.54099	18885.4728	0.333%	192	102	40	26
129	0.0001	24871	0.01	248.71	30	35	710.60	100	30%	50%	100	40043.94	1372.17	29.18293	41416.11022	41360.0439	0.135%	34	102	42	26
130	0.0001	24871	0.01	248.71	30	35	710.60	100	30%	50%	150	58115.68	1501.17	38.71359	59616.8452	59553.2655	0.107%	29	102	46	30
131	0.0001	24871	0.01	248.71	30	35	710.60	500	30%	50%	1	4482.321	5324.47	0.841834	9806.790706	9784.04499	0.232%	794	102	35	21
132	0.0001	24871	0.01	248.71	30	35	710.60	500	30%	50%	10	7087.83	5331.65	1.329388	12419.48043	12357.9896	0.495%	858	102	35	20
133	0.0001	24871	0.01	248.71	30	35	710.60	500	30%	50%	50	17878.27	5494.05	3.254115	23372.31808	23255.6626	0.499%	3250	102	36	22
134	0.0001	24871	0.01	248.71	30	35	710.60	500	30%	50%	100	40432.56	5655.85	7.148803	46088.41016	45865.861	0.483%	626	102	37	22

135	0.0001	24871	0.01	248.71	30	35	710.60	500	30%	50%	150	58882.63	5650.85	10.42014	64533.48252	64240.2902	0.454%	307	102	37	21
136	0.0001	24871	0.01	248.71	30	35	710.60	1000	30%	50%	1	4482.321	10574.47	0.423881	15056.79071	15034.045	0.151%	792	102	35	21
137	0.0001	24871	0.01	248.71	30	35	710.60	1000	30%	50%	10	7087.83	10581.65	0.669823	17669.48043	17601.2139	0.386%	782	102	35	20
138	0.0001	24871	0.01	248.71	30	35	710.60	1000	30%	50%	50	18033.69	10600.58	1.701198	28634.26859	28514.6524	0.418%	2682	102	35	23
139	0.0001	24871	0.01	248.71	30	35	710.60	1000	30%	50%	100	40960.71	10593.45	3.866607	51554.1571	51281.8426	0.528%	3721	107	35	20
140	0.0001	24871	0.01	248.71	30	35	710.60	1000	30%	50%	150	58809.58	11207.14	5.24751	70016.71623	69767.6385	0.356%	2599	102	37	23
141	0.0001	24871	0.01	248.71	30	35	710.60	5000	30%	50%	1	4482.321	52574.47	0.085257	57056.79071	57034.045	0.040%	830	102	35	21
142	0.0001	24871	0.01	248.71	30	35	710.60	5000	30%	50%	10	7087.83	52581.65	0.134797	59669.48043	59601.2139	0.114%	834	102	35	20
143	0.0001	24871	0.01	248.71	30	35	710.60	5000	30%	50%	50	18073.49	52591.22	0.34366	70664.71046	70466.3335	0.281%	1103	102	35	21
144	0.0001	24871	0.01	248.71	30	35	710.60	5000	30%	50%	100	40960.71	52593.45	0.778818	93554.1571	93175.1037	0.405%	684	102	35	20
145	0.0001	24871	0.01	248.71	30	35	710.60	5000	30%	50%	150	59620.94	52597.39	1.133534	112218.3267	111681.781	0.478%	688	102	35	20
146	0.0001	24871	0.01	248.71	30	35	710.60	10000	30%	50%	1	4482.321	105074.5	0.042659	109556.7907	109534.045	0.021%	861	102	35	21
147	0.0001	24871	0.01	248.71	30	35	710.60	10000	30%	50%	10	7087.83	105081.7	0.067451	112169.4804	112101.214	0.061%	825	102	35	20
148	0.0001	24871	0.01	248.71	30	35	710.60	10000	30%	50%	50	18073.49	105091.2	0.171979	123164.7105	122966.333	0.161%	1151	102	35	21
149	0.0001	24871	0.01	248.71	30	35	710.60	10000	30%	50%	100	40960.71	105093.5	0.389755	146054.1571	145675.104	0.260%	609	102	35	20
150	0.0001	24871	0.01	248.71	30	35	710.60	10000	30%	50%	150	59620.94	105097.4	0.567292	164718.3267	164181.781	0.326%	705	102	35	20
151	0.0001	24871	0.05	1243.55	30	133	187.00	10	30%	50%	1	22058.88	694.44	31.76499	22753.322	22726.9878	0.116%	65	102	134	43
152	0.0001	24871	0.05	1243.55	30	133	187.00	10	30%	50%	10	34498.03	721.7	47.80107	35219.73064	35192.4586	0.077%	44	102	136	46
153	0.0001	24871	0.05	1243.55	30	133	187.00	10	30%	50%	50	87665.56	773.15	113.3875	88438.70743	88383.9921	0.062%	35	102	143	51
154	0.0001	24871	0.05	1243.55	30	133	187.00	10	30%	50%	100	199436.1	755.48	263.9859	200191.5366	200081.768	0.055%	35	102	141	49
155	0.0001	24871	0.05	1243.55	30	133	187.00	10	30%	50%	150	290095.2	765.49	378.9667	290860.7311	290777.413	0.029%	37	102	143	50
156	0.0001	24871	0.05	1243.55	30	133	187.00	100	30%	50%	1	22079.44	4280.44	5.158216	26359.8755	26321.1742	0.147%	138	102	133	43
157	0.0001	24871	0.05	1243.55	30	133	187.00	100	30%	50%	10	34512.3	4329.94	7.970618	38842.23793	38792.2926	0.129%	63	102	134	45
158	0.0001	24871	0.05	1243.55	30	133	187.00	100	30%	50%	50	87790.45	4340	20.22821	92130.44564	92019.4312	0.121%	48	102	134	48
159	0.0001	24871	0.05	1243.55	30	133	187.00	100	30%	50%	100	199440.6	4499.83	44.3218	203940.3856	203727.351	0.105%	48	102	139	49
160	0.0001	24871	0.05	1243.55	30	133	187.00	100	30%	50%	150	290291.6	4393.83	66.06802	294685.4809	294419.015	0.090%	46	102	136	48
161	0.0001	24871	0.05	1243.55	30	133	187.00	500	30%	50%	1	22079.44	20240.44	1.090857	42319.8755	42281.1742	0.091%	140	102	133	43
162	0.0001	24871	0.05	1243.55	30	133	187.00	500	30%	50%	10	34540.9	20257.14	1.705122	54798.03657	54752.2926	0.084%	83	102	133	45
163	0.0001	24871	0.05	1243.55	30	133	187.00	500	30%	50%	50	87866.24	20267.2	4.335391	108133.4447	107986.876	0.136%	79	102	133	48
164	0.0001	24871	0.05	1243.55	30	133	187.00	500	30%	50%	100	199691.6	20419.15	9.779623	220110.7324	219765.128	0.157%	55	102	134	48
165	0.0001	24871	0.05	1243.55	30	133	187.00	500	30%	50%	150	290291.7	20713.83	14.01439	311005.4809	310462.311	0.175%	52	102	136	48
166	0.0001	24871	0.05	1243.55	30	133	187.00	1000	30%	50%	1	22079.44	40190.44	0.54937	62269.8755	62231.1742	0.062%	138	102	133	43
167	0.0001	24871	0.05	1243.55	30	133	187.00	1000	30%	50%	10	34540.9	40207.14	0.859074	74748.03657	74702.2926	0.061%	82	102	133	45
168	0.0001	24871	0.05	1243.55	30	133	187.00	1000	30%	50%	50	87866.24	40217.2	2.184793	128083.4447	127936.876	0.114%	77	102	133	48
169	0.0001	24871	0.05	1243.55	30	133	187.00	1000	30%	50%	100	199657.5	40518.69	4.92754	240176.1428	239741.927	0.181%	81	102	134	47
170	0.0001	24871	0.05	1243.55	30	133	187.00	1000	30%	50%	150	290506.7	40510.72	7.171107	331017.4299	330505.968	0.155%	55	102	134	46
171	0.0001	24871	0.05	1243.55	30	133	187.00	5000	30%	50%	1	22079.44	199790.4	0.110513	221869.8755	221831.174	0.017%	136	102	133	43
172	0.0001	24871	0.05	1243.55	30	133	187.00	5000	30%	50%	10	34540.9	199807.1	0.172871	234348.0366	234302.293	0.020%	82	102	133	45
173	0.0001	24871	0.05	1243.55	30	133	187.00	5000	30%	50%	50	87866.24	199817.2	0.439733	287683.4447	287536.876	0.051%	77	102	133	48
174	0.0001	24871	0.05	1243.55	30	133	187.00	5000	30%	50%	100	199933.1	199816.8	1.000582	399749.9291	399341.927	0.102%	93	102	133	47
175	0.0001	24871	0.05	1243.55	30	133	187.00	5000	30%	50%	150	290878.4	199809.3	1.45578	490687.6935	490120.577	0.116%	99	102	133	46
176	0.0001	24871	0.05	1243.55	30	133	187.00	10000	30%	50%	1	22079.44	399290.4	0.055297	421369.8755	421331.174	0.009%	138	102	133	43
177	0.0001	24871	0.05	1243.55	30	133	187.00	10000	30%	50%	10	34540.9	399307.1	0.086502	433848.0366	433802.293	0.011%	81	102	133	45
178	0.0001	24871	0.05	1243.55	30	133	187.00	10000	30%	50%	50	87866.24	399317.2	0.220041	487183.4447	487036.876	0.030%	76	102	133	48
179	0.0001	24871	0.05	1243.55	30	133	187.00	10000	30%	50%	100	199933.1	399316.8	0.500688	599249.9291	598841.927	0.068%	98	102	133	47
180	0.0001	24871	0.05	1243.55	30	133	187.00	10000	30%	50%	150	290878.4	399309.3	0.728454	690187.6935	689620.577	0.082%	100	102	133	46
181	0.0001	24871	0.1	2487.1	30	248	100.29	10	30%	50%	1	44076.11	1293.45	34.07639	45369.55607	45336.108	0.074%	52	102	251	47
182	0.0001	24871	0.1	2487.1	30	248	100.29	10	30%	50%	10	68975.36	1337.16	51.58347	70312.51751	70250.0086	0.089%	49	102	253	49
183	0.0001	24871	0.1	2487.1	30	248	100.29	10	30%	50%	50	175361.5	1368.36	128.1545	176729.8981	176615.685	0.065%	37	102	254	53
184	0.0001	24871	0.1	2487.1	30	248	100.29	10	30%	50%	100	398887.5	1353.45	294.719	400240.9007	400017.94	0.056%	39	102	255	52
185	0.0001	24871	0.1	2487.1	30	248	100.29	10	30%	50%	150	580564.1	1342.41	432.4789	581906.4764	581415.077	0.084%	41	102	253	51
186	0.0001	24871	0.1	2487.1	30	248	100.29	100	30%	50%	1	44106.13	7970.48	5.533685	52076.60675	52032.1497	0.085%	77	102	248	47
187	0.0001	24871	0.1	2487.1	30	248	100.29	100	30%	50%	10	69028.43	8000.61	8.627896	77029.03945	76948.4062	0.105%	55	102	248	49
188	0.0001	24871	0.1	2487.1	30	248	100.29	100	30%	50%	50	175483.1	8059.56	21.77328	183542.6319	183344.955	0.108%	44	102	249	51
189	0.0001	24871	0.1	2487.1	30	248	100.29	100	30%	50%	100	399021.2	8141.71	49.00951	407162.8912	406748.238	0.102%	51	102	252	52
190	0.0001	24871	0.1	2487.1	30	248	100.29	100	30%	50%	150	580636.8	8034.69	72.26623	588671.4725	588126.498	0.093%	43	102	249	49
191	0.0001	24871	0.1	2487.1	30	248	100.29	500	30%	50%	1	44106.13	37730.48	1.168979	81836.60675	81792.1497	0.054%	76	102	248	47
192	0.0001	24871	0.1	2487.1	30	248	100.29	500	30%	50%	10	69031.47	37763.1	1.828014	106794.5739	106708.406	0.081%	64	102	248	49
193	0.0001	24871	0.1	2487.1	30	248	100.29	500	30%	50%	50	175577	37784.75	4.646769	213361.7423	213104.955	0.120%	71	102	248	52
194	0.0001	24871	0.1	2487.1	30	248	100.29	500	30%	50%	100	399337.7	37767.94	10.57346	437105.644	436501.411	0.138%	53	102	248	51
195	0.0001	24871	0.1	2487.1	30	248	100.29	500	30%	50%	150	580639.2	37914.11	15.31459	618553.3158	617902.72	0.105%	48	102	249	49
196	0.0001	24871	0.1	2487.1	30	248	100.29	1000	30%	50%	1	44106.13	74930.48	0.588627	119036.6068	118992.15	0.037%	76	102	248	47
197	0.0001	24871	0.1	2487.1	30	248	100.29	1000	30%	50%	10	69031.47	74963.1	0.920873	143994.5739	143908.406	0.060%	65	102	248	49
198	0.0001	24871	0.1	2487.1	30	248	100.29	1000	30%	50%	50	175554.7	74988.9	2.341076	250543.6142	250304.955	0.095%	74	102	248	51
199	0.0001	24871	0.1	2487.1	30	248	100.29	1000	30%	50%	100	399337.7	74967.94	5.32678	474305.644	473709.835	0.126%	82	102	248	51
200	0.0001	24871	0.1	2487.1	30	248	100.29	1000	30%	50%	150	580921.4	74959.94	7.749758	655881.3696	655116.107	0.117%	50	102	248	49
201	0.0001	24871	0.1	2487.1	30	248	100.29	5000	30%	50%	1	44106.13	372530.5	0.118396	416636.6068	416592.15	0.011%	76	102	248	47
202	0.0001	24871	0.1	2487.1	30	248	100.29	5000	30%	50%	10	69031.47	372563.1	0.185288	441594.5739	441508.406	0.020%	64	102	248	49
203	0.0001	24871	0.1	2487.1	30	248	100.29	5000	30%	50%	50	175554.7	372588.9	0.471175	548143.6142	547904.955	0.044%	75	102	248	51
204	0.0001	24871	0.1	2487.1	30	248	100.29	5000	30%	50%	100	399333.4	372568.7	1.071838	771902.0392	771309.835	0.077%	81	102	248	51
205	0.0001	24871	0.1	2487.1	30	248	100.29	5000	30%	50%	150	581034.6	372558.5	1.559579	953593.1231	952737.207	0.090%	59	102	248	49
206	0.0001	24871	0.1	2487.1	30	248	100.29	10000	30%	50%	1	44106.13	744530.5	0.05924	788636.6068	788592.15	0.006%	76	102	248	47

207	0.0001	24871	0.1	2487.1	30	248	100.29	10000	30%	50%	10	69031.47	744563.1	0.092714	813594.5739	813508.406	0.011%	65	102	248	49
208	0.0001	24871	0.1	2487.1	30	248	100.29	10000	30%	50%	50	175554.7	744588.9	0.235774	920143.6142	919904.955	0.026%	74	102	248	51
209	0.0001	24871	0.1	2487.1	30	248	100.29	10000	30%	50%	100	399333.4	744568.7	0.536328	1143902.039	1143309.83	0.052%	82	102	248	51
210	0.0001	24871	0.1	2487.1	30	248	100.29	10000	30%	50%	150	581034.6	744558.5	0.780375	1325593.123	1324737.21	0.065%	58	102	248	49

* 101 means optimal, 102 means within 0.5%, and 107 means timeout.

Appendix A2. Stocking Solution.

ZIP	CITY	ST	Facility	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
15108	Coraopolis	PA	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19061	Chester	PA	2	0	1	1	1	1	0	1	1	0	1	0	1	1	0	1	0	1	1	0	1	0	1	1	0	1	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
23150	Sandston	VA	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23228	Richmond	VA	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23513	Norfolk	VA	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24012	Roanoke	VA	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25143	Nitro	WV	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27284	Kernersville	NC	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27703	Durham	NC	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28269	Charlotte	NC	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29201	Columbia	SC	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29577	Myrtle Beach	SC	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30349	Atlanta	GA	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31407	Port Wentworth	GA	14	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0	1	0	0	1	1	0	0	0	1	1	0	0	0	1	1	0	0	0	1	1	0	0
31904	Columbus	GA	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32256	Jacksonville	FL	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32837	Orlando	Fl	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33312	Ft Lauderdale	FL	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33634	Tampa	FL	19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33905	Fort Myers	FL	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35209	Birmingham	AL	21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35805	Huntsville	AL	22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
36303	Dothan	AL	23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
36606	Mobile	AL	24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37214	Nashville	TN	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37923	Knoxville	TN	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
38118	Memphis	TN	27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
39202	Jackson	MS	28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
40219	Louisville	KY	29 (CW)	2	1	1	1	1	2	1	1	2	1	2	1	1	2	1	2	1	1	2	1	2	1	1	2	1	2	1	1	2	1	3	1	1	1	1	3	1	1	2	2	3	1	1	3	3	3	1	1	3	3	3	1	1	3	3	3	1	1	3	3
41018	Erlanger	KY	30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43229	Columbus	OH	31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
44141	Brecksville	OH	32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
46808	Ft Wayne	IN	33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
47715	Evansville	IN	34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48150	Livonia	MI	35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48917	Lansing	MI	36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
49548	Grand Rapids	MI	37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
52807	Davenport	IA	38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
53151	New Berlin	WI	39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
55112	Arden Hills	MN	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
60007	Elk Grove Village	IL	41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
60176	Schiller Park	IL	42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
63026	Fenton	MO	43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
64120	Kansas City	MO	44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
65109	Jefferson City	MO	45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
67211	Wichita	KS	46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
68106	Omaha	NE	47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
70002	Metairie	LA	48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
70663	Sulpher	LA	49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
70806	Baton Rouge	LA	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
72209	Little Rock	AR	51	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
72712	Bentonville	AR	52	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
73108	Oklahoma City	OK	53	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
74128	Tulsa	OK	54	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
74145	Tulsa	OK	55	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0
75229	Dallas	TX	56	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	1	1	1	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0
77032	Houston	TX	57	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
78247	San Antonio	TX	58	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
78744	Austin	TX	59	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
79925	El Paso	TX	60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
80216	Denver	CO	61	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
80907	Colorado Springs	CO	62	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
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84119	Salt Lake City	UT	64	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
85282	Tempe	AZ	65	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
85710	Tuscon	AZ	66	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
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92111	San Diego	CA	71	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
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93003	Ventura	CA	74	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	0	0	0	1	1	0	0	0	1	1	0	0	0	1	1
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98188	Tukwila	WA	78	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
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201	202	203	204	205	206	207	208	209	210	SUM	CITY	ST	Facility
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58	52	41	53	53	58	52	41	53	53	2905	Louisville	KY	29 (CW)
0	0	2	0	0	0	0	2	0	0	22	Erlanger	KY	30
2	4	9	3	4	2	4	9	3	4	194	Columbus	OH	31
0	3	3	3	2	0	3	3	3	2	156	Brecksville	OH	32
0	0	0	0	0	0	0	0	0	0	0	Ft Wayne	IN	33
0	0	4	0	0	0	0	4	0	0	38	Evansville	IN	34
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3	4	4	4	4	3	4	4	4	4	185	Grand Rapids	MI	37
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0	0	1	1	0	0	0	1	1	0	35	Sulpher	LA	49
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1	1	1	1	1	1	1	1	1	1	104	Little Rock	AR	51
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3	1	1	1	1	3	1	1	1	1	81	Oklahoma City	OK	53
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2	2	2	2	2	2	2	2	2	2	136	Austin	TX	59
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4	4	3	3	3	4	4	3	3	3	184	Denver	CO	61
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4	4	4	4	4	4	4	4	4	4	207	Tempe	AZ	65
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1	1	1	1	1	1	1	1	1	1	90	Albuquerque	NM	67
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1	1	0	1	1	1	1	0	1	1	68	Los Angeles	CA	69
0	0	0	0	0	0	0	0	0	0	3	Ontario	CA	70
0	0	0	0	0	0	0	0	0	0	13	San Diego	CA	71
0	0	0	0	0	0	0	0	0	0	1	Santa Ana	CA	72
18	18	19	18	18	18	18	19	18	18	975	Santa Ana	CA	73
0	0	0	0	0	0	0	0	0	0	21	Ventura	CA	74
0	0	0	0	0	0	0	0	0	0	2	Burlingame	CA	75
11	11	11	11	11	11	11	11	11	11	621	W Sacramento	CA	76
7	7	7	7	7	7	7	7	7	7	404	Portland	OR	77
0	0	0	0	0	0	0	0	0	0	0	Tukwila	WA	78
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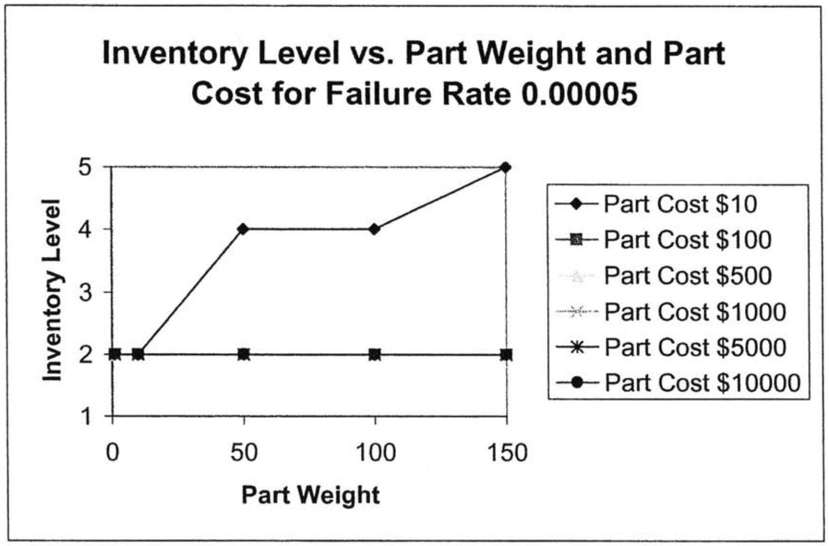
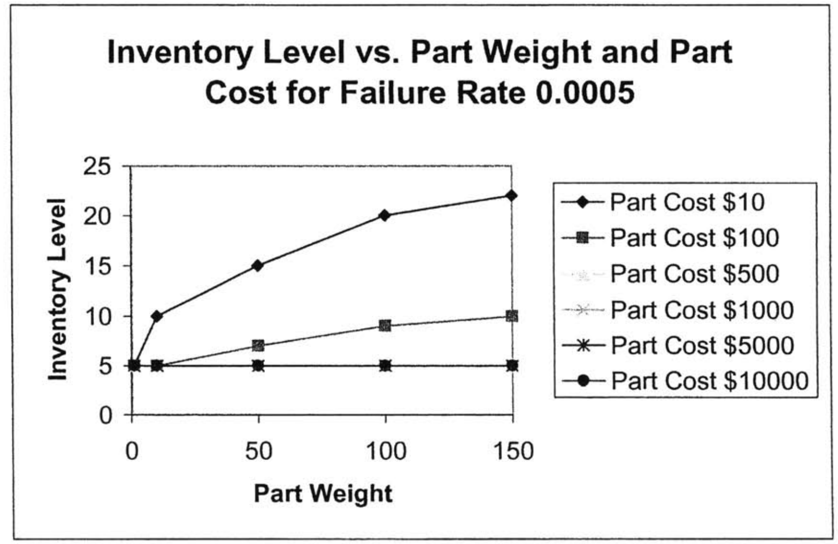
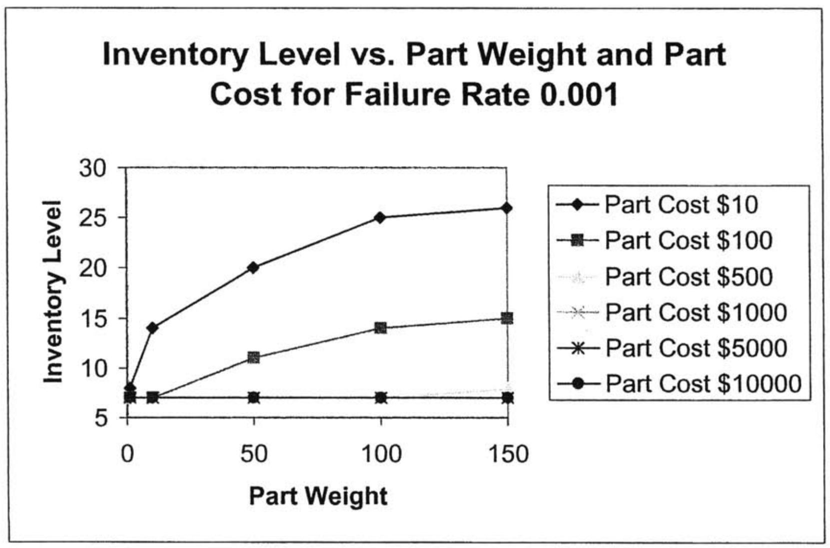
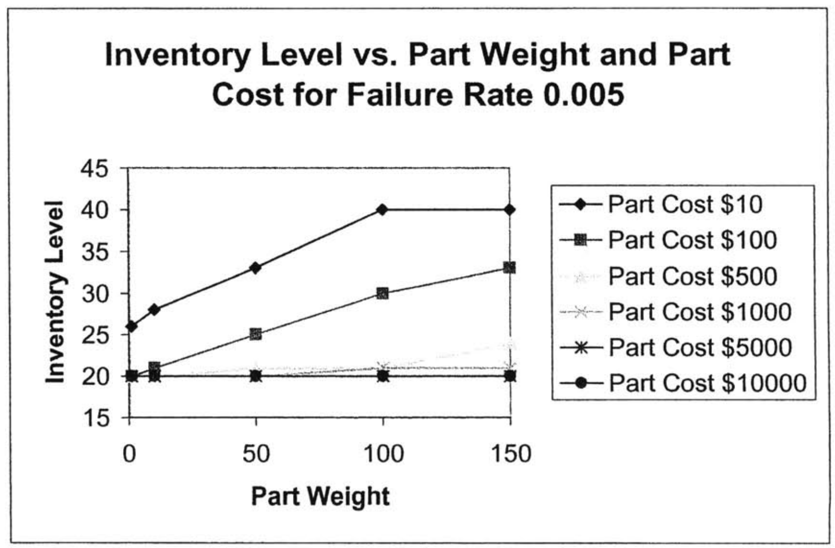
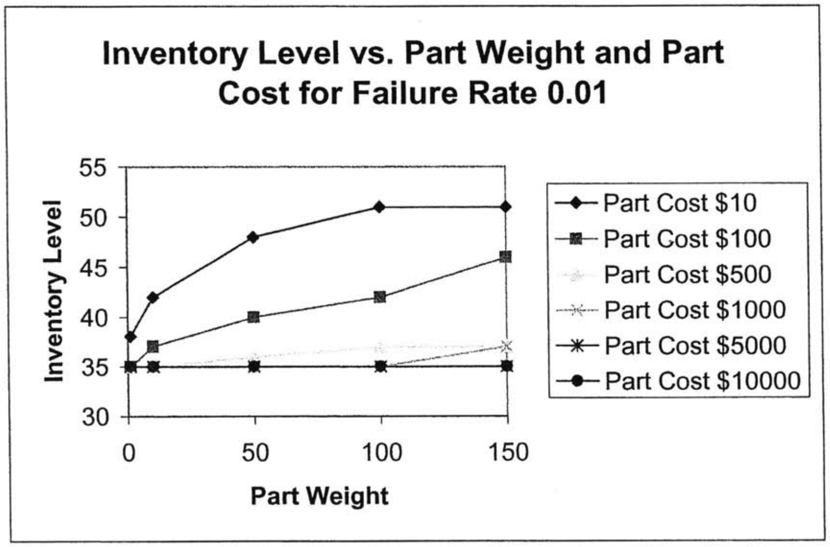
Appendix A3. Inventory Level Analysis.

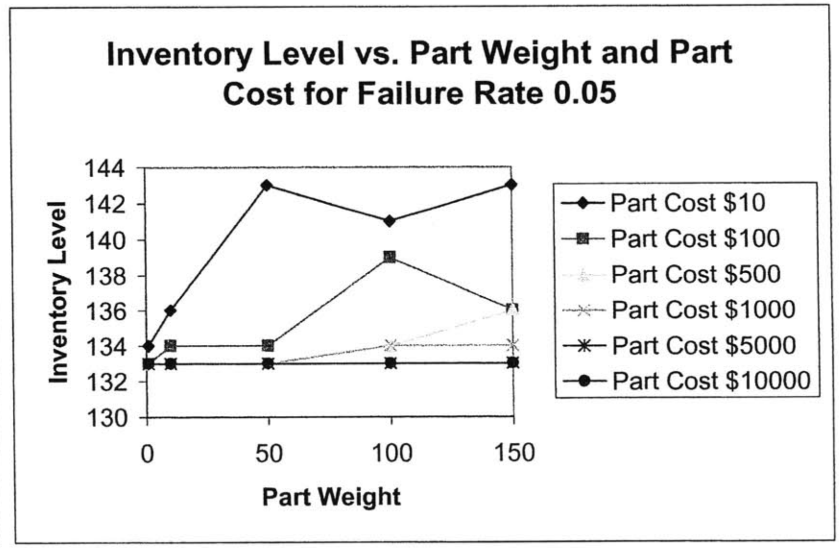


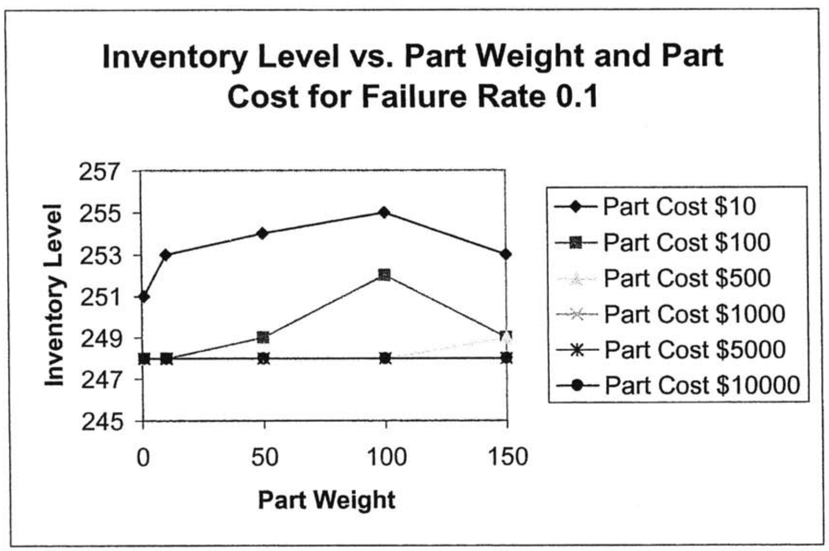




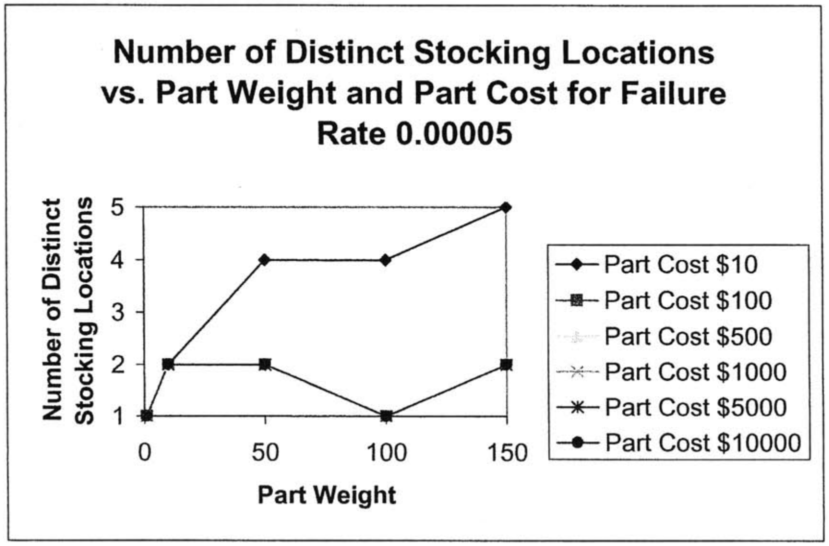


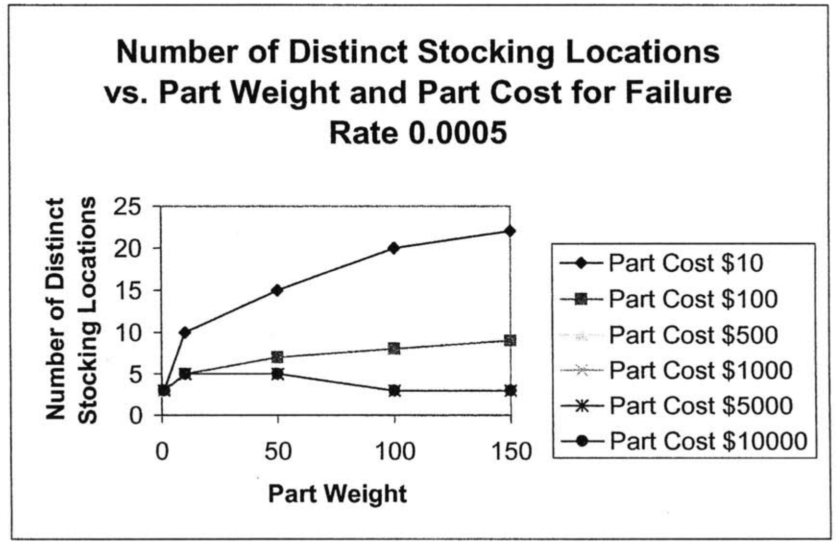

Inventory Level vs. Part Weight and Part Cost for Failure Rate 0.01
Inventory Level
Part Weight
55
50
45
40
35
30
0
50
100
150
Part Cost $10
Part Cost $100
Part Cost $500
Part Cost $1000
Part Cost $5000
Part Cost $10000

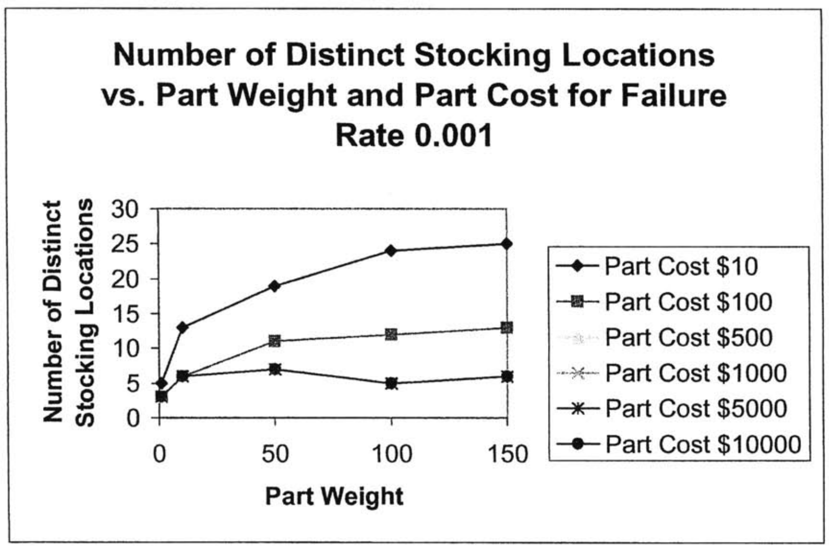

Inventory Level vs. Part Weight and Part Cost for Failure Rate 0.05
Inventory Level
Part Weight
144
142
140
138
136
134
132
130
0
50
100
150
Part Cost $10
Part Cost $100
Part Cost $500
Part Cost $1000
Part Cost $5000
Part Cost $10000

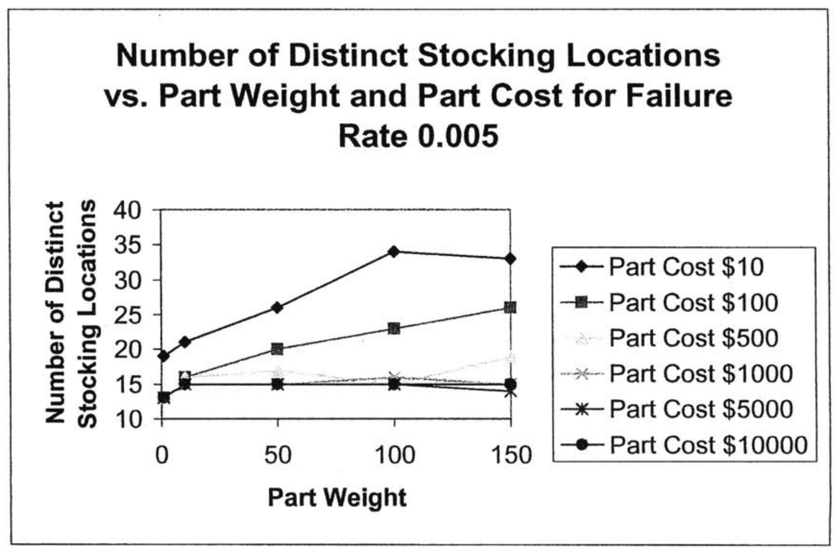

Inventory Level vs. Part Weight and Part Cost for Failure Rate 0.1
Inventory Level
Part Weight
257
255
253
251
249
247
245
0
50
100
150
Part Cost $10
Part Cost $100
Part Cost $500
Part Cost $1000
Part Cost $5000
Part Cost $10000

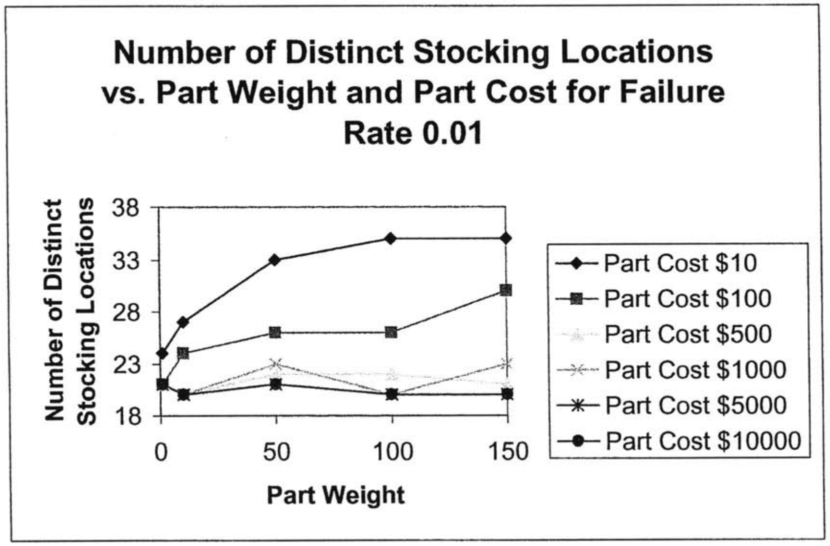
Appendix A4. Distinct Stocking Locations Analysis.

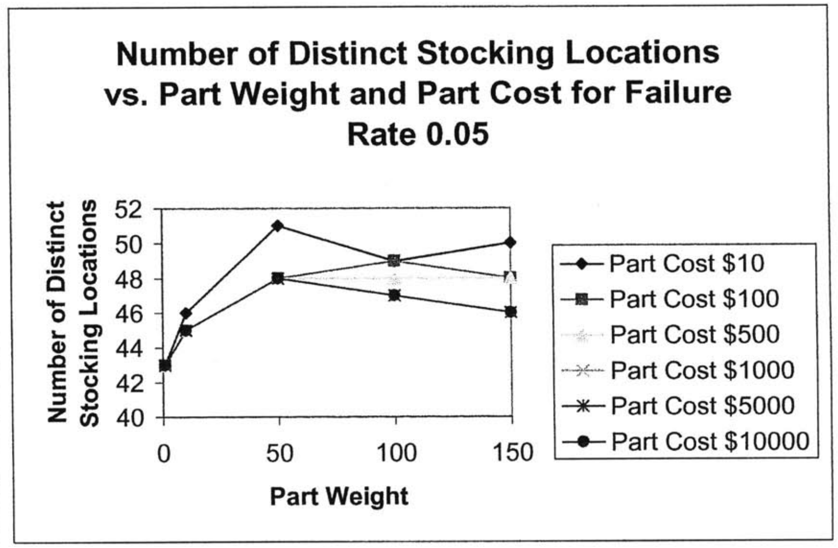


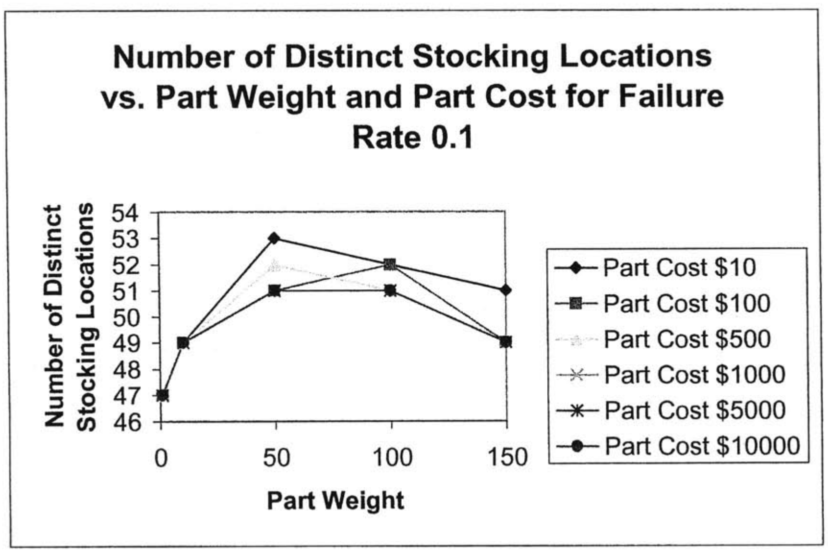




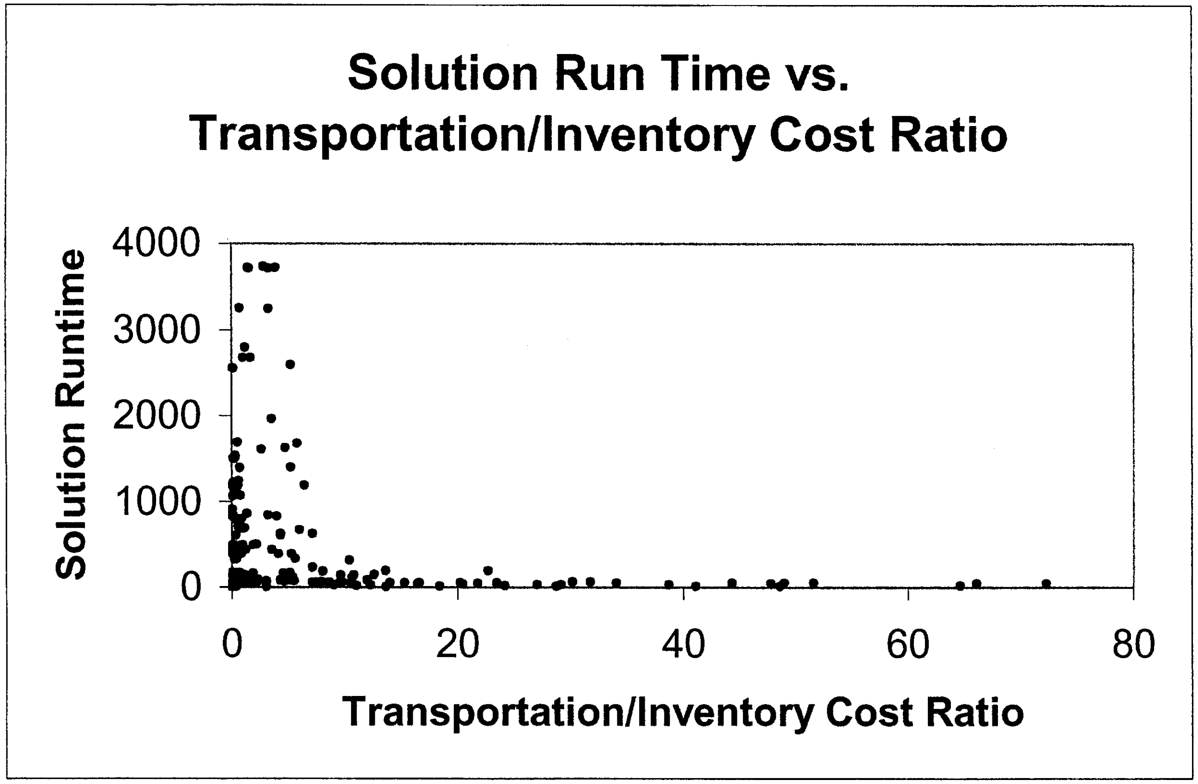



Number of Distinct Stocking Locations vs. Part Weight and Part Cost for Failure Rate 0.01
Number of Distinct Stocking Locations
38
33
28
23
18
0
50
100
150
Part Weight
Part Cost $10
Part Cost $100
Part Cost $500
Part Cost $1000
Part Cost $5000
Part Cost $10000


Number of Distinct Stocking Locations vs. Part Weight and Part Cost for Failure Rate 0.05
Number of Distinct Stocking Locations
52
50
48
46
44
42
40
0
50
100
150
Part Weight
Part Cost $10
Part Cost $100
Part Cost $500
Part Cost $1000
Part Cost $5000
Part Cost $10000


Number of Distinct Stocking Locations vs. Part Weight and Part Cost for Failure Rate 0.1
Number of Distinct Stocking Locations
54
53
52
51
50
49
48
47
46
0
50
100
150
Part Weight
Part Cost $10
Part Cost $100
Part Cost $500
Part Cost $1000
Part Cost $5000
Part Cost $10000

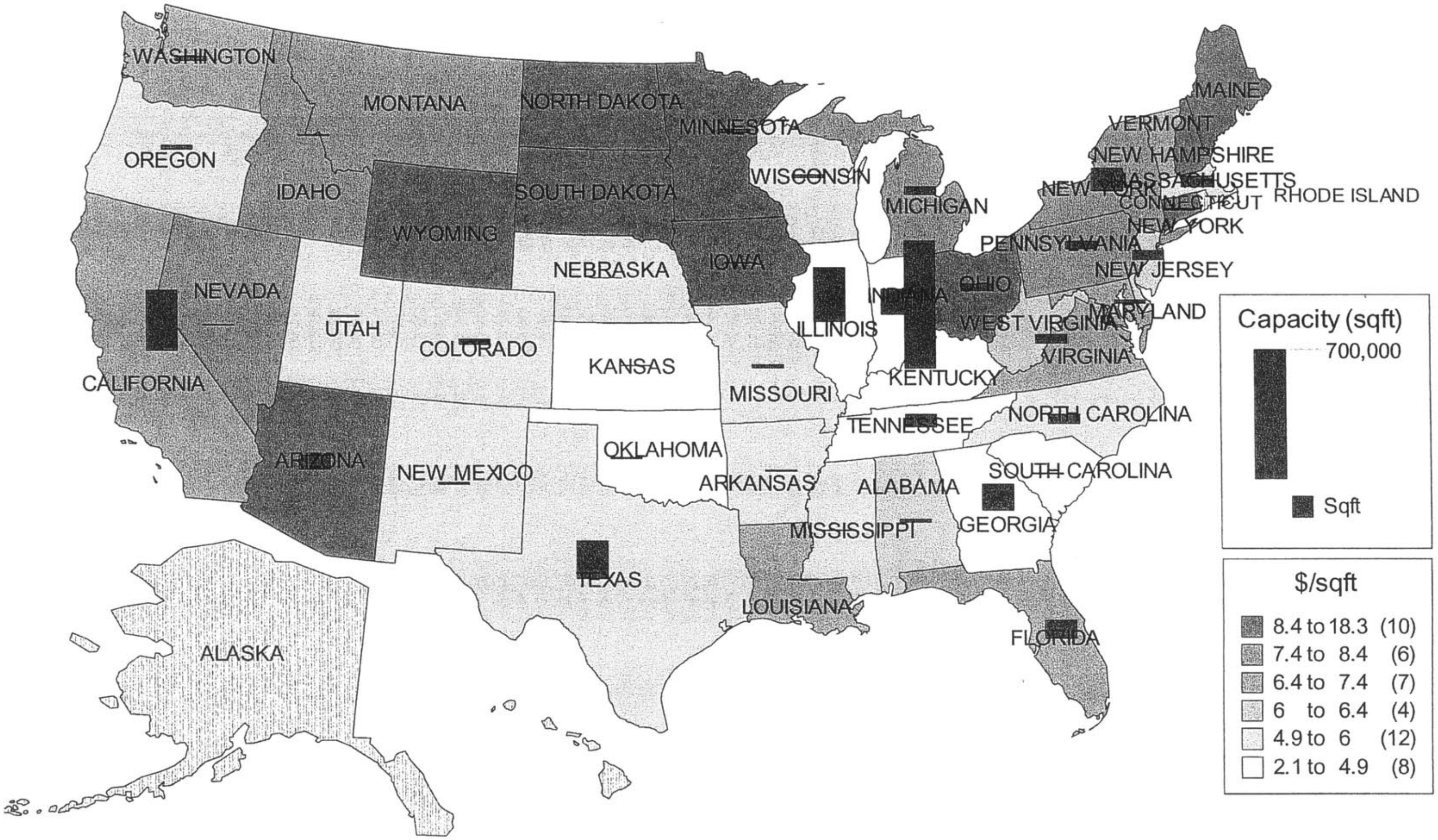
Appendix A5. Solution Run Times.



Appendix B1. FSL Capacity and Rent/Sqft

		Capacity	Fixed Cost	$/ft^2
AL	Alabama	26130	166060	6.35514734
AR	Arkansas	14750	80424	5.452474576
AZ	Arizona	82472	1124615	13.63632506
CA	California	333756	2407703	7.213961697
CO	Colorado	37420	209913	5.609647247
CT	Connecticut	16408	161696	9.854705022
DE	Delaware	3700	22767	6.153243243
FL	Florida	106434	708943	6.660869647
GA	Georgia	146814	555585	3.784278066
IA	Iowa	11400	97678	8.568245614
ID	Idaho	11704	88560	7.566643882
IL	Illinois	297029	1234696	4.156819704
IN	Indiana	141934	504593	3.555124213
KS	Kansas	9800	26100	2.663265306
KY	Kentucky	692135	1453508	2.100035398
LA	Louisiana	13976	102465	7.331496852
MA	Massachusetts	67761	399348	5.89347855
MD	Maryland	27271	200164	7.339811521
ME	Maine	3045	26159	8.590804598
MI	Michigan	49730	383999	7.721677056
MN	Minnesota	25601	220921	8.629389477
MO	Missouri	27974	163137	5.831736613
MS	Mississippi	10000	56000	5.6
MT	Montana	1360	10080	7.411764706
NC	N Carolina	58066	345979	5.958374953
ND	N Dakota	1443	19901	13.79140679
NE	Nebraska	10000	56000	5.6
NH	New Hampshire	697	10800	15.49497848
NJ	New Jersey	55769	354897	6.363696677
NM	New Mexico	17891	104928	5.864848248
NV	Nevada	16000	128000	8
NY	New York	128915	1073178	8.324694566
OH	Ohio	44673	376169	8.420500078
OK	Oklahoma	15900	56683	3.564968553
OR	Oregon	28341	166717	5.882537666
PA	Pennsylvania	47651	396187	8.314348072
SC	S Carolina	15170	62826	4.141463415
SD	S Dakota	751	13729	18.28095872
TN	Tennessee	76100	264748	3.478948752
TX	Texas	213205	1061583	4.979165592
UT	Utah	15020	74048	4.929960053
VA	Virginia	56847	379281	6.671961581
VT	Vermont	4800	34128	7.11
WA	Washington	32891	241035	7.328296494
WI	Wisconsin	24916	149480	5.999357842
WV	West Virginia	3750	22500	6
WY	Wyoming	217	3255	15

Appendix B2. FSL Network.



Appendix C1. Generic SKU Groups.

Population 248709873

Index	Installation %Population	# Installations	Failure Rate	Expected # Failures (annual)	Supplier Leadtime (days)	Minimum Inventory (CW)	Sharing Factor	Part Cost	Part Weight (lbs)
1	0.0001	24871	0.0001	2.4871	30	2	12435.50	10	1
2	0.0001	24871	0.0001	2.4871	30	2	12435.50	10	10
3	0.0001	24871	0.0001	2.4871	30	2	12435.50	10	50
4	0.0001	24871	0.0001	2.4871	30	2	12435.50	10	150
5	0.0001	24871	0.0001	2.4871	30	2	12435.50	100	1
6	0.0001	24871	0.0001	2.4871	30	2	12435.50	100	10
7	0.0001	24871	0.0001	2.4871	30	2	12435.50	100	50
8	0.0001	24871	0.0001	2.4871	30	2	12435.50	100	150
9	0.0001	24871	0.0001	2.4871	30	2	12435.50	500	1
10	0.0001	24871	0.0001	2.4871	30	2	12435.50	500	10
11	0.0001	24871	0.0001	2.4871	30	2	12435.50	500	50
12	0.0001	24871	0.0001	2.4871	30	2	12435.50	500	150
13	0.0001	24871	0.0001	2.4871	30	2	12435.50	1000	1
14	0.0001	24871	0.0001	2.4871	30	2	12435.50	1000	10
15	0.0001	24871	0.0001	2.4871	30	2	12435.50	1000	50
16	0.0001	24871	0.0001	2.4871	30	2	12435.50	1000	150
17	0.0001	24871	0.001	24.871	30	7	3553.00	10	1
18	0.0001	24871	0.001	24.871	30	7	3553.00	10	10
19	0.0001	24871	0.001	24.871	30	7	3553.00	10	50
20	0.0001	24871	0.001	24.871	30	7	3553.00	10	150
21	0.0001	24871	0.001	24.871	30	7	3553.00	100	1
22	0.0001	24871	0.001	24.871	30	7	3553.00	100	10
23	0.0001	24871	0.001	24.871	30	7	3553.00	100	50
24	0.0001	24871	0.001	24.871	30	7	3553.00	100	150
25	0.0001	24871	0.001	24.871	30	7	3553.00	500	1
26	0.0001	24871	0.001	24.871	30	7	3553.00	500	10
27	0.0001	24871	0.001	24.871	30	7	3553.00	500	50
28	0.0001	24871	0.001	24.871	30	7	3553.00	500	150
29	0.0001	24871	0.001	24.871	30	7	3553.00	1000	1
30	0.0001	24871	0.001	24.871	30	7	3553.00	1000	10
31	0.0001	24871	0.001	24.871	30	7	3553.00	1000	50
32	0.0001	24871	0.001	24.871	30	7	3553.00	1000	150
33	0.0001	24871	0.01	248.71	30	35	710.60	10	1
34	0.0001	24871	0.01	248.71	30	35	710.60	10	10
35	0.0001	24871	0.01	248.71	30	35	710.60	10	50
36	0.0001	24871	0.01	248.71	30	35	710.60	10	150
37	0.0001	24871	0.01	248.71	30	35	710.60	100	1
38	0.0001	24871	0.01	248.71	30	35	710.60	100	10
39	0.0001	24871	0.01	248.71	30	35	710.60	100	50
40	0.0001	24871	0.01	248.71	30	35	710.60	100	150
41	0.0001	24871	0.01	248.71	30	35	710.60	500	1
42	0.0001	24871	0.01	248.71	30	35	710.60	500	10
43	0.0001	24871	0.01	248.71	30	35	710.60	500	50
44	0.0001	24871	0.01	248.71	30	35	710.60	500	150
45	0.0001	24871	0.01	248.71	30	35	710.60	1000	1
46	0.0001	24871	0.01	248.71	30	35	710.60	1000	10
47	0.0001	24871	0.01	248.71	30	35	710.60	1000	50
48	0.0001	24871	0.01	248.71	30	35	710.60	1000	150
49	0.0001	24871	0.1	2487.1	30	248	100.29	10	1
50	0.0001	24871	0.1	2487.1	30	248	100.29	10	10
51	0.0001	24871	0.1	2487.1	30	248	100.29	10	50
52	0.0001	24871	0.1	2487.1	30	248	100.29	10	150
53	0.0001	24871	0.1	2487.1	30	248	100.29	100	1
54	0.0001	24871	0.1	2487.1	30	248	100.29	100	10
55	0.0001	24871	0.1	2487.1	30	248	100.29	100	50
56	0.0001	24871	0.1	2487.1	30	248	100.29	100	150
57	0.0001	24871	0.1	2487.1	30	248	100.29	500	1
58	0.0001	24871	0.1	2487.1	30	248	100.29	500	10
59	0.0001	24871	0.1	2487.1	30	248	100.29	500	50
60	0.0001	24871	0.1	2487.1	30	248	100.29	500	150
61	0.0001	24871	0.1	2487.1	30	248	100.29	1000	1
62	0.0001	24871	0.1	2487.1	30	248	100.29	1000	10
63	0.0001	24871	0.1	2487.1	30	248	100.29	1000	50
64	0.0001	24871	0.1	2487.1	30	248	100.29	1000	150

Appendix C2. Real Parts Distribution Across Generic SKU Groups.

F1: 0.0001

		Weight				
		1	**10**	**50**	**150**	**Total**
Cost	**10**	4088	834	3	0	4925
	100	653	655	849	247	2404
	500	53	150	83	180	466
	1000	29	14	29	48	120
	Total	4823	1653	964	475	7915

F2: 0.001

		Weight				
		1	**10**	**50**	**150**	**Total**
Cost	**10**	1224	263	0	0	1487
	100	143	144	127	19	433
	500	10	8	5	29	52
	1000	1	2	3	8	14
	Total	1378	417	135	56	1986

F3: 0.01

		Weight				
		1	**10**	**50**	**150**	**Total**
Cost	**10**	989	207	0	0	1196
	100	66	50	47	5	168
	500	2	2	0	16	20
	1000	0	0	1	0	1
	Total	1057	259	48	21	1385

F4: 0.1

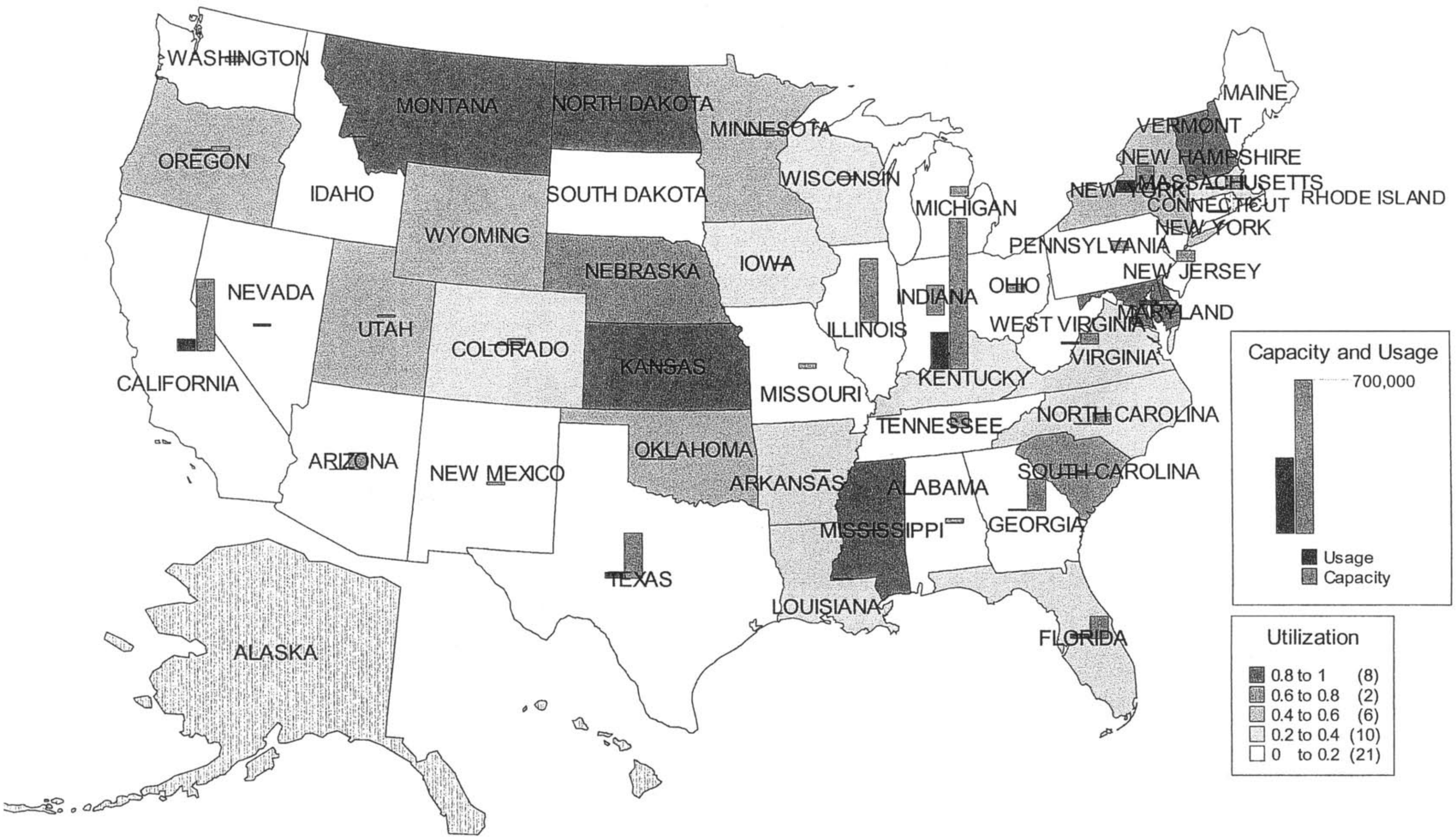
		Weight				
		1	**10**	**50**	**150**	**Total**
Cost	**10**	349	41	0	0	390
	100	5	6	15	1	27
	500	0	0	0	8	8
	1000	0	0	0	0	0
	Total	354	47	15	9	425

Appendix C3. Inventory Optimization Summary

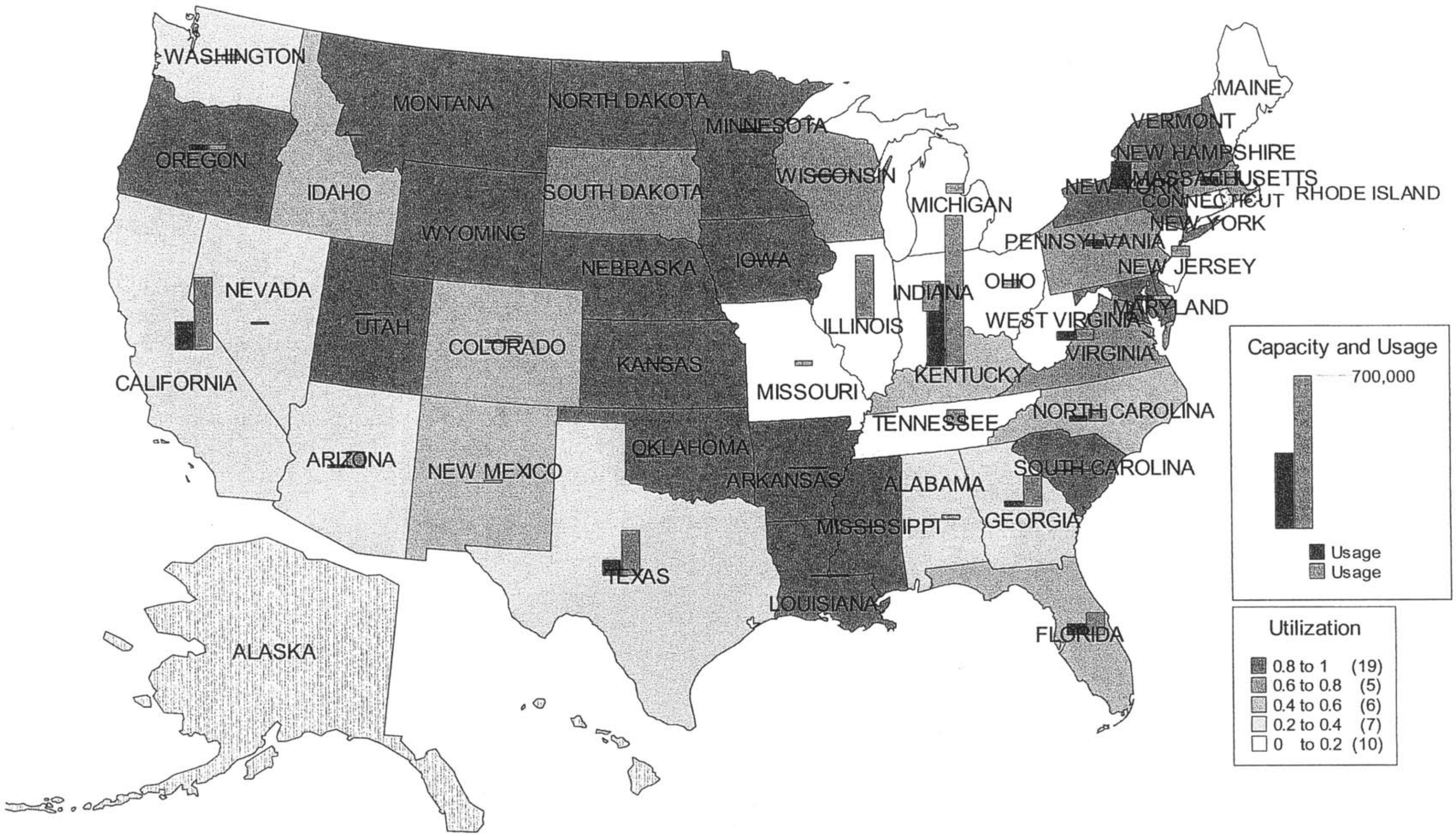
			20% Volume		40% Volume		60% Volume		80% Volume	
State Code	**State Name**	**Capacity**	**Usage**	**Utilization**	**Usage**	**Utilization**	**Usage**	**Utilization**	**Usage**	**Utilization**
AL	Alabama	26130	1300	5%	7368.87	28%	26003.9	100%	23219.8	89%
AR	Arkansas	14750	3603	24%	12229.6	83%	14750	100%	14750	100%
AZ	Arizona	82472	9900	12%	21100	26%	30658.3	37%	41938.4	51%
CA	California	333756	61200	18%	133500	40%	198968	60%	273931	82%
CO	Colorado	37420	10300	28%	21783	58%	32500	87%	37420	100%
CT	Connecticut	16408	0	0%	900	5%	0	0%	1649.18	10%
DE	Delaware	3700	3700	100%	3700	100%	3700	100%	3700	100%
FL	Florida	106434	26200	25%	57000	54%	84300	79%	106004	100%
GA	Georgia	146814	13700	9%	29866.1	20%	48279.8	33%	146814	100%
IA	Iowa	11400	4100	36%	10700	94%	11400	100%	11400	100%
ID	Idaho	11704	1940	17%	5940	51%	11704	100%	11704	100%
IL	Illinois	297029	200	0%	835.563	0%	7153.18	2%	85352.7	29%
IN	Indiana	141934	297	0%	1435.56	1%	875.94	1%	91161.2	64%
KS	Kansas	9800	8500	87%	9800	100%	9800	100%	9800	100%
KY	Kentucky	692135	174503	25%	375422	54%	648166	94%	692135	100%
LA	Louisiana	13976	4800	34%	12119.9	87%	13976	100%	13976	100%
MA	Massachusetts	67761	15344.1	23%	42481	63%	67761	100%	67761	100%
MD	Maryland	27271	27271	100%	27271	100%	27271	100%	27271	100%
ME	Maine	3045	0	0%	0	0%	0	0%	310.003	10%
MI	Michigan	49730	1900	4%	6800	14%	18019.8	36%	41490.6	83%
MN	Minnesota	25601	10800	42%	22696.4	89%	25601	100%	25203.3	98%
MO	Missouri	27974	1700	6%	5590.23	20%	22098.1	79%	27810	99%
MS	Mississippi	10000	9600	96%	10000	100%	10000	100%	9337.59	93%
MT	Montana	1360	1360	100%	1360	100%	1360	100%	1360	100%
NC	N Carolina	58066	13203	23%	29682	51%	49543.7	85%	58066	100%
ND	N Dakota	1443	1200	83%	1443	100%	1443	100%	1443	100%
NE	Nebraska	10000	7000	70%	10000	100%	10000	100%	10000	100%
NH	New Hampshire	697	697	100%	697	100%	697	100%	697	100%
NJ	New Jersey	55769	0	0%	0	0%	751	1%	14138.7	25%
NM	New Mexico	17891	3300	18%	7300	41%	11158.4	62%	17891	100%
NV	Nevada	16000	1200	8%	4200	26%	5150.47	32%	10540	66%
NY	New York	128915	60880	47%	128915	100%	128915	100%	128915	100%
OH	Ohio	44673	0	0%	0	0%	0	0%	6069.46	14%
OK	Oklahoma	15900	8200	52%	15900	100%	15900	100%	15900	100%
OR	Oregon	28341	15600	55%	27733.9	98%	27226.8	96%	28341	100%
PA	Pennsylvania	47651	5286.72	11%	37101.3	78%	47651	100%	47651	100%
SC	S Carolina	15170	10500	69%	13898.3	92%	15170	100%	15170	100%
SD	S Dakota	751	0	0%	512.113	68%	751	100%	751	100%
TN	Tennessee	76100	0	0%	900	1%	1502	2%	72047.4	95%
TX	Texas	213205	32500	15%	75235.6	35%	112054	53%	147498	69%
UT	Utah	15020	6800	45%	14200	95%	15020	100%	15020	100%
VA	Virginia	56847	17801.2	31%	44646.4	79%	56847	100%	56847	100%
VT	Vermont	4800	4655.8	97%	4800	100%	4800	100%	4800	100%
WA	Washington	32891	0	0%	7261.84	22%	23709.5	72%	32891	100%
WI	Wisconsin	24916	6241.2	25%	17800	71%	24916	100%	24916	100%
WV	West Virginia	3750	200	5%	600	16%	1100	29%	3750	100%
WY	Wyoming	217	100	46%	217	100%	200	92%	217	100%

Solution Run Time (seconds)	282	734	1216	2230
Total Cost	$ 1,116,550	$ 3,336,140	$ 4,548,800	$ 6,228,960

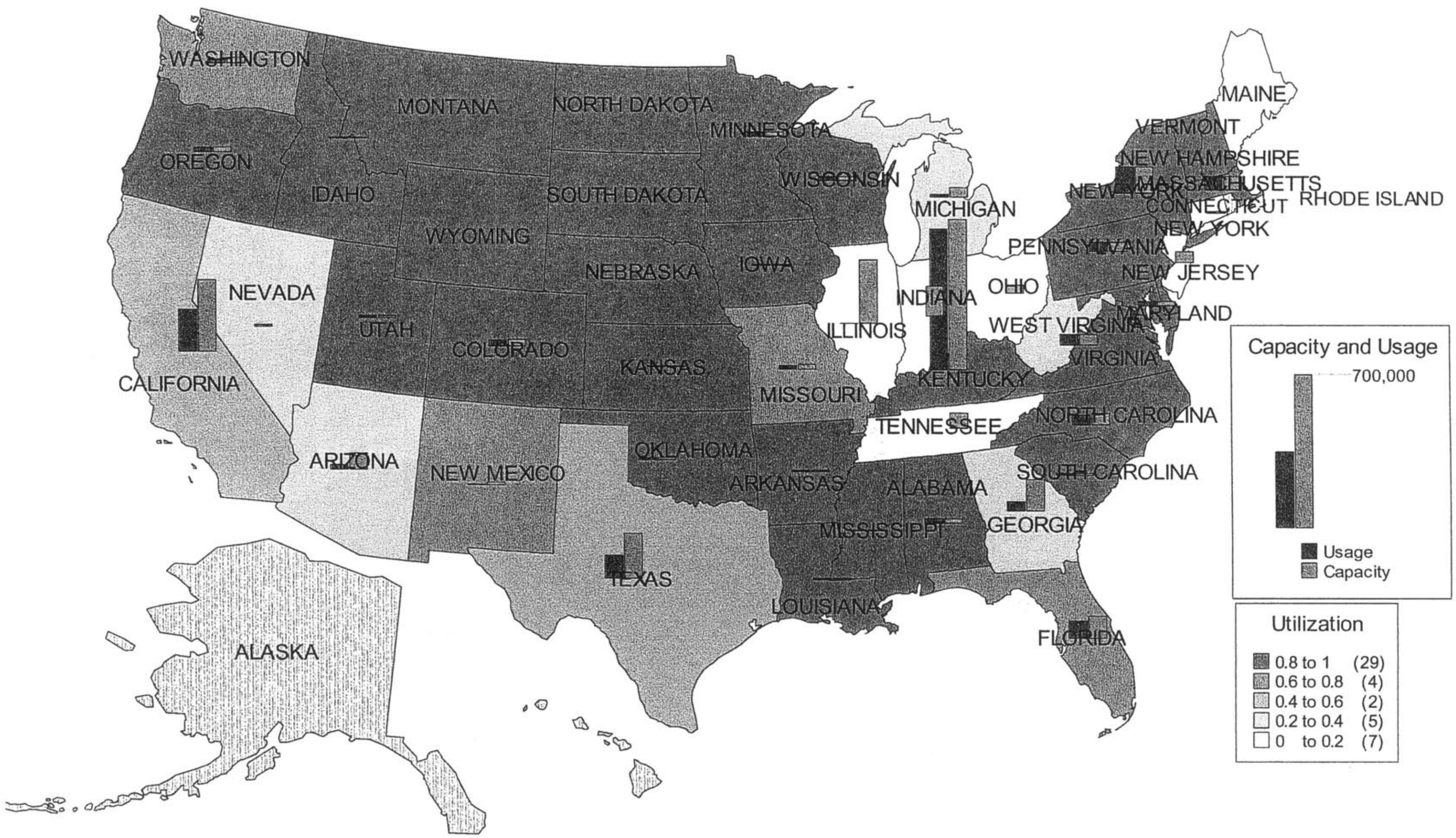
Appendix C4. Inventory Optimization at 20% Volume.



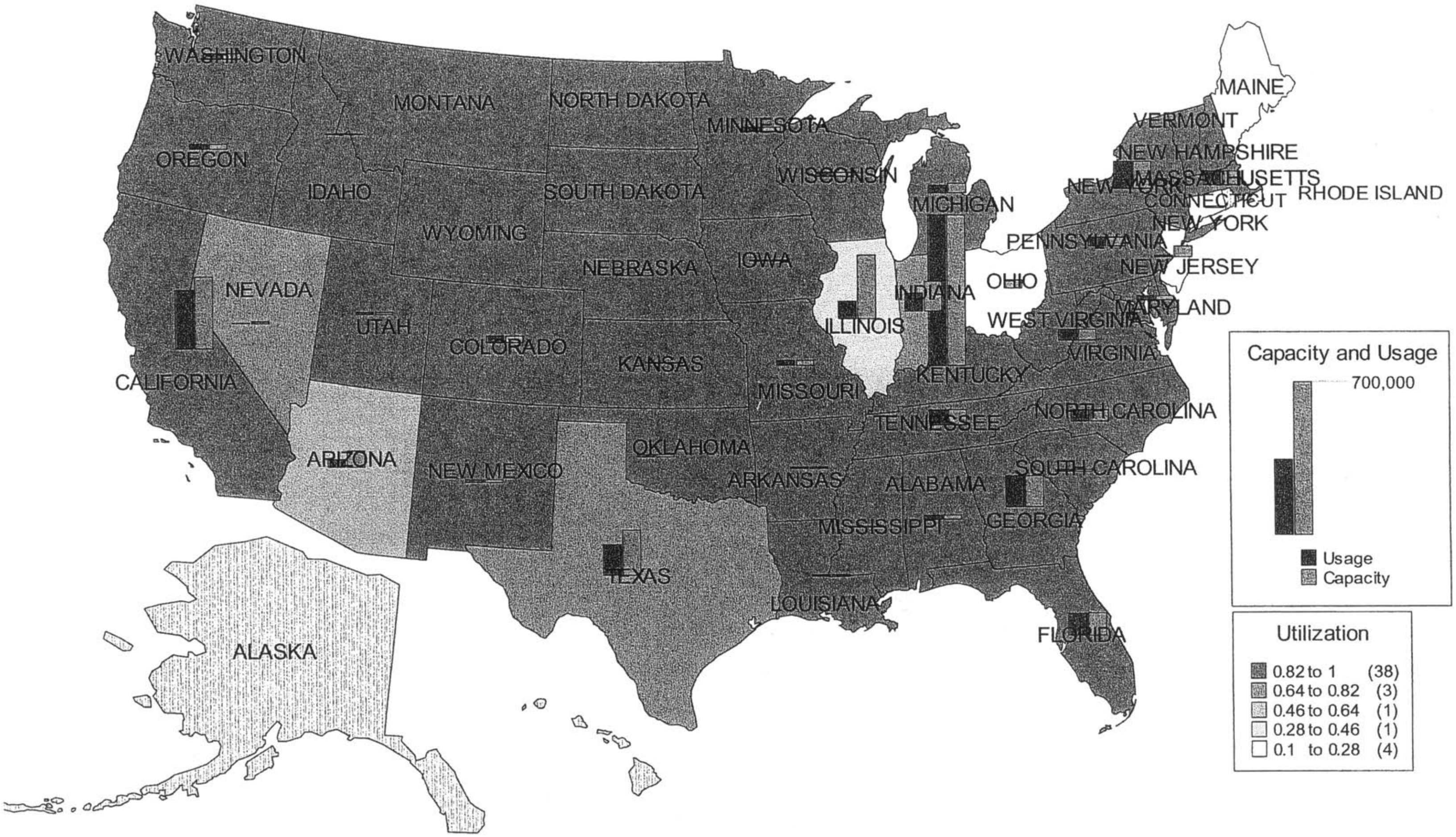
Appendix C5. Inventory Optimization at 40% Volume.



Appendix C6. Inventory Optimization at 60% Volume.



Appendix C7. Inventory Optimization at 80% Volume.

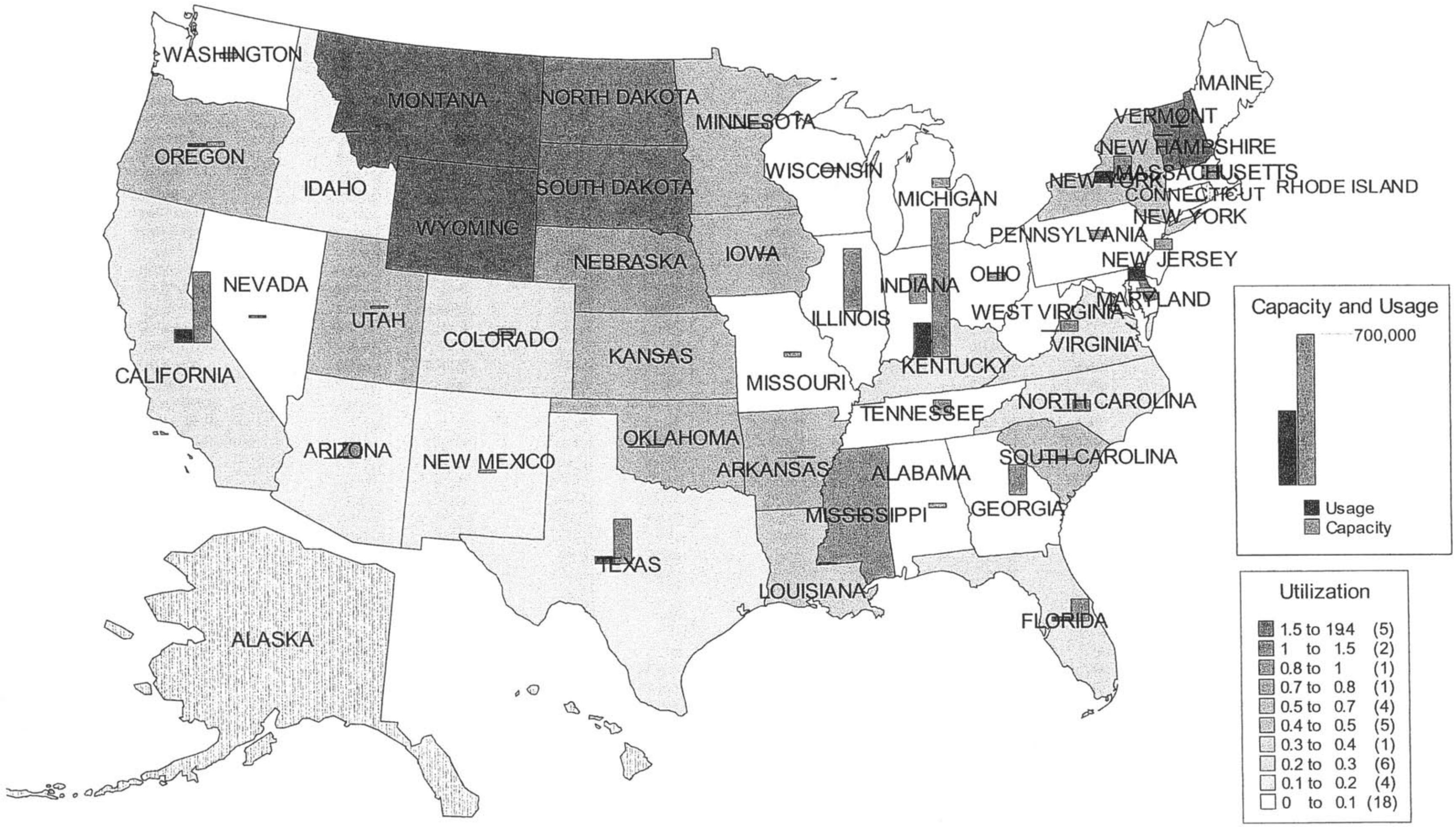


Appendix D1. Unconstrained Plan Summary

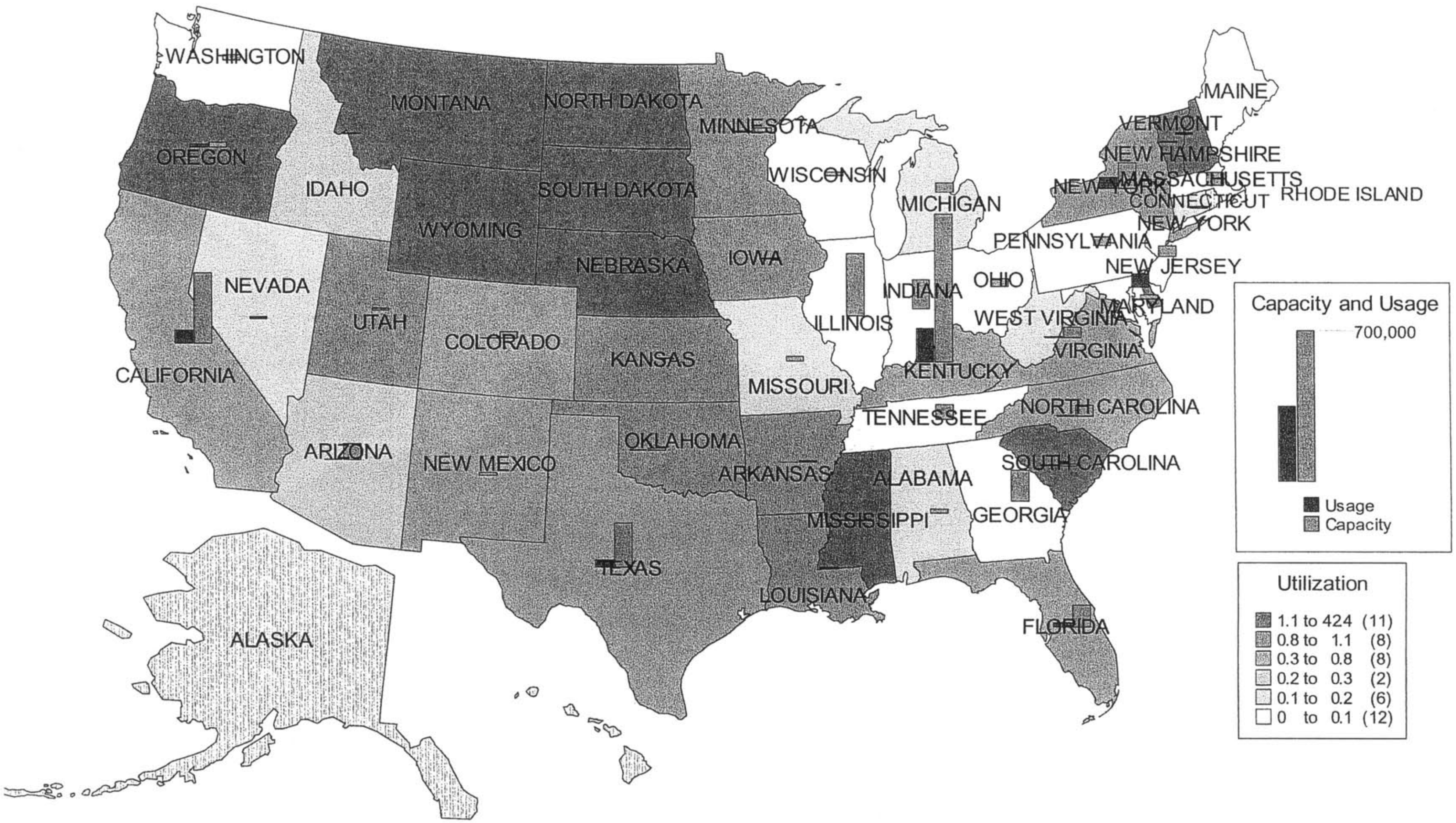
			20% Volume		40% Volume		60% Volume		80% Volume		100% Volume	
State Code	**State Name**	**Capacity**	**Usage**	**Utilization**	**Usage**	**Utilization**	**Usage**	**Utilization**	**Usage**	**Utilization**	**Usage**	**Utilization**
AL	Alabama	26130	1700	7%	4500	17%	6500	25%	8700	33%	10800	41%
AR	Arkansas	14750	7600	52%	16200	110%	23900	162%	32200	218%	40100	272%
AZ	Arizona	82472	10400	13%	22000	27%	32700	40%	44100	53%	54900	67%
CA	California	333756	67100	20%	145300	44%	215000	64%	291100	87%	361300	108%
CO	Colorado	37420	7900	21%	16800	45%	24900	67%	33500	90%	41800	112%
CT	Connecticut	16408	900	5%	1700	10%	2600	16%	3400	21%	4300	26%
DE	Delaware	3700	68200	1843%	147200	3978%	219300	5927%	294600	7962%	367600	9935%
FL	Florida	106434	26200	25%	57000	54%	84300	79%	114300	107%	141800	133%
GA	Georgia	146814	400	0%	600	0%	1000	1%	1400	1%	1700	1%
IA	Iowa	11400	4800	42%	10700	94%	15700	138%	21500	189%	26600	233%
ID	Idaho	11704	1200	10%	2800	24%	4100	35%	5600	48%	6900	59%
IL	Illinois	297029	0	0%	0	0%	0	0%	0	0%	0	0%
IN	Indiana	141934	0	0%	0	0%	0	0%	0	0%	0	0%
KS	Kansas	9800	4600	47%	10200	104%	15100	154%	20500	209%	25400	259%
KY	Kentucky	692135	163300	24%	344500	50%	510900	74%	690700	100%	858000	124%
LA	Louisiana	13976	4800	34%	11200	80%	16400	117%	22400	160%	27600	197%
MA	Massachusetts	67761	0	0%	0	0%	0	0%	0	0%	0	0%
MD	Maryland	27271	0	0%	600	2%	1100	4%	1700	6%	1700	6%
ME	Maine	3045	0	0%	0	0%	0	0%	0	0%	0	0%
MI	Michigan	49730	2600	5%	6800	14%	10100	20%	12700	26%	16100	32%
MN	Minnesota	25601	10800	42%	22800	89%	33900	132%	45800	179%	57000	223%
MO	Missouri	27974	1700	6%	4600	16%	6700	24%	8900	32%	11000	39%
MS	Mississippi	10000	9600	96%	20000	200%	29800	298%	40200	402%	50100	501%
MT	Montana	1360	2100	154%	4500	331%	6600	485%	9000	662%	11200	824%
NC	N Carolina	58066	13000	22%	28600	49%	42200	73%	57300	99%	71000	122%
ND	N Dakota	1443	2100	146%	4500	312%	6600	457%	9000	624%	11200	776%
NE	Nebraska	10000	7500	75%	15500	155%	23100	231%	31200	312%	38900	389%
NH	New Hampshire	697	13500	1937%	29500	4232%	43600	6255%	59200	8494%	73400	10531%
NJ	New Jersey	55769	0	0%	0	0%	0	0%	0	0%	0	0%
NM	New Mexico	17891	3300	18%	7300	41%	10700	60%	14500	81%	18000	101%
NV	Nevada	16000	1400	9%	3100	19%	4600	29%	6200	39%	7700	48%
NY	New York	128915	58500	45%	126100	98%	185100	144%	252700	196%	312200	242%
OH	Ohio	44673	0	0%	0	0%	0	0%	0	0%	0	0%
OK	Oklahoma	15900	8200	52%	17400	109%	25800	162%	34900	219%	43400	273%
OR	Oregon	28341	19600	69%	42000	148%	62300	220%	84200	297%	104600	369%
PA	Pennsylvania	47651	0	0%	0	0%	0	0%	0	0%	0	0%
SC	S Carolina	15170	10300	68%	21900	144%	32400	214%	43700	288%	54500	359%
SD	S Dakota	751	1100	146%	2400	320%	3500	466%	4900	652%	6000	799%
TN	Tennessee	76100	0	0%	100	0%	100	0%	200	0%	200	0%
TX	Texas	213205	39800	19%	85600	40%	126800	59%	171600	80%	213200	100%
UT	Utah	15020	6600	44%	13900	93%	20600	137%	27700	184%	34600	230%
VA	Virginia	56847	13000	23%	28500	50%	42000	74%	57000	100%	70700	124%
VT	Vermont	4800	10600	221%	23000	479%	34000	708%	46100	960%	57200	1192%
WA	Washington	32891	0	0%	0	0%	0	0%	0	0%	0	0%
WI	Wisconsin	24916	0	0%	0	0%	0	0%	100	0%	100	0%
WV	West Virginia	3750	200	5%	600	16%	1000	27%	1200	32%	1600	43%
WY	Wyoming	217	2500	1152%	5200	2396%	7800	3594%	10600	4885%	13100	6037%

	20% Volume	40% Volume	60% Volume	80% Volume	100% Volume
Solution Run Time (seconds)	70	97	98	104	104
Total Cost	$ 1,113,420	$ 3,337,180	$ 4,526,450	$ 6,136,210	$ 7,319,910

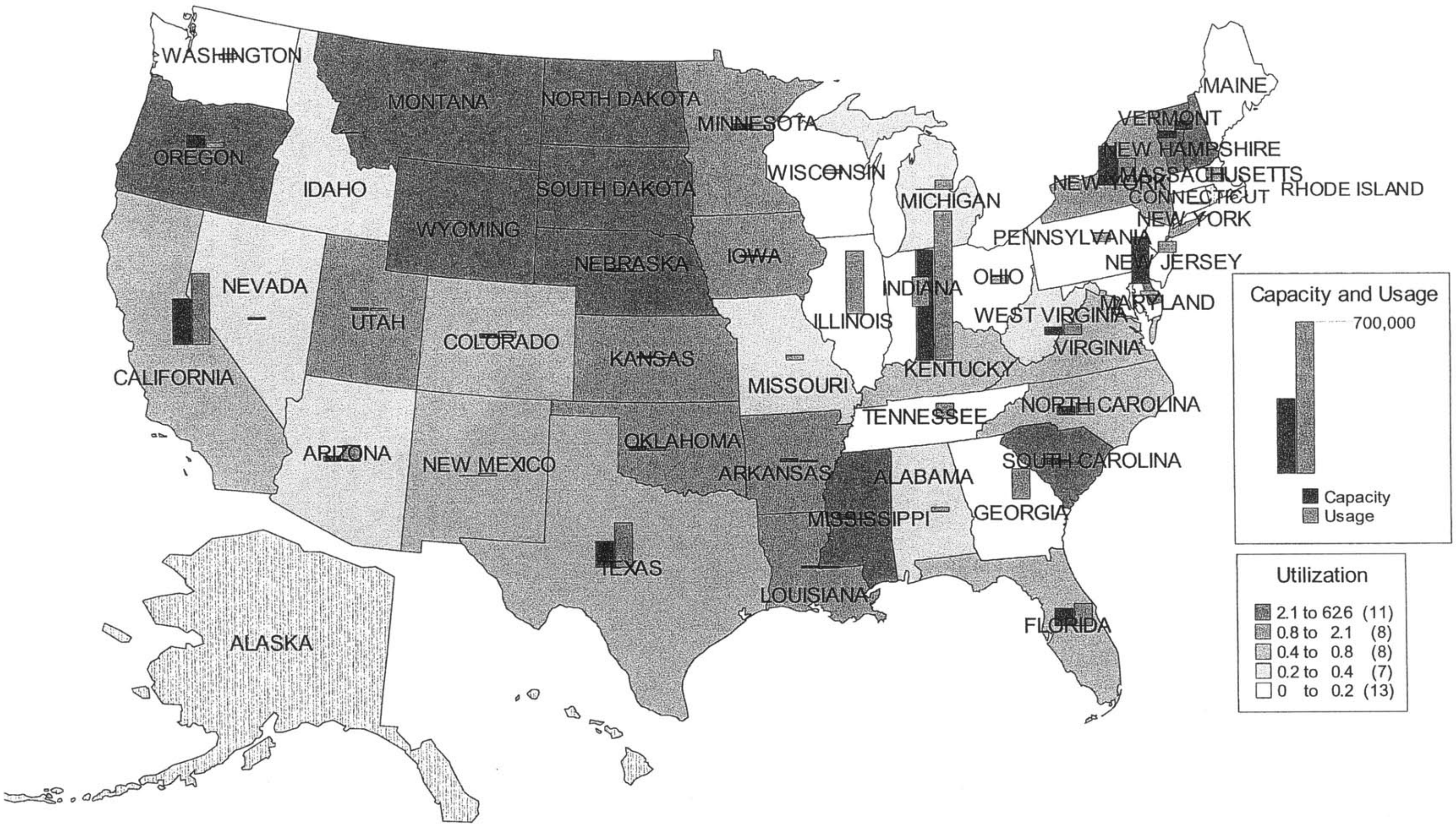
Appendix D2. Unconstrained Plan at 20% Volume.



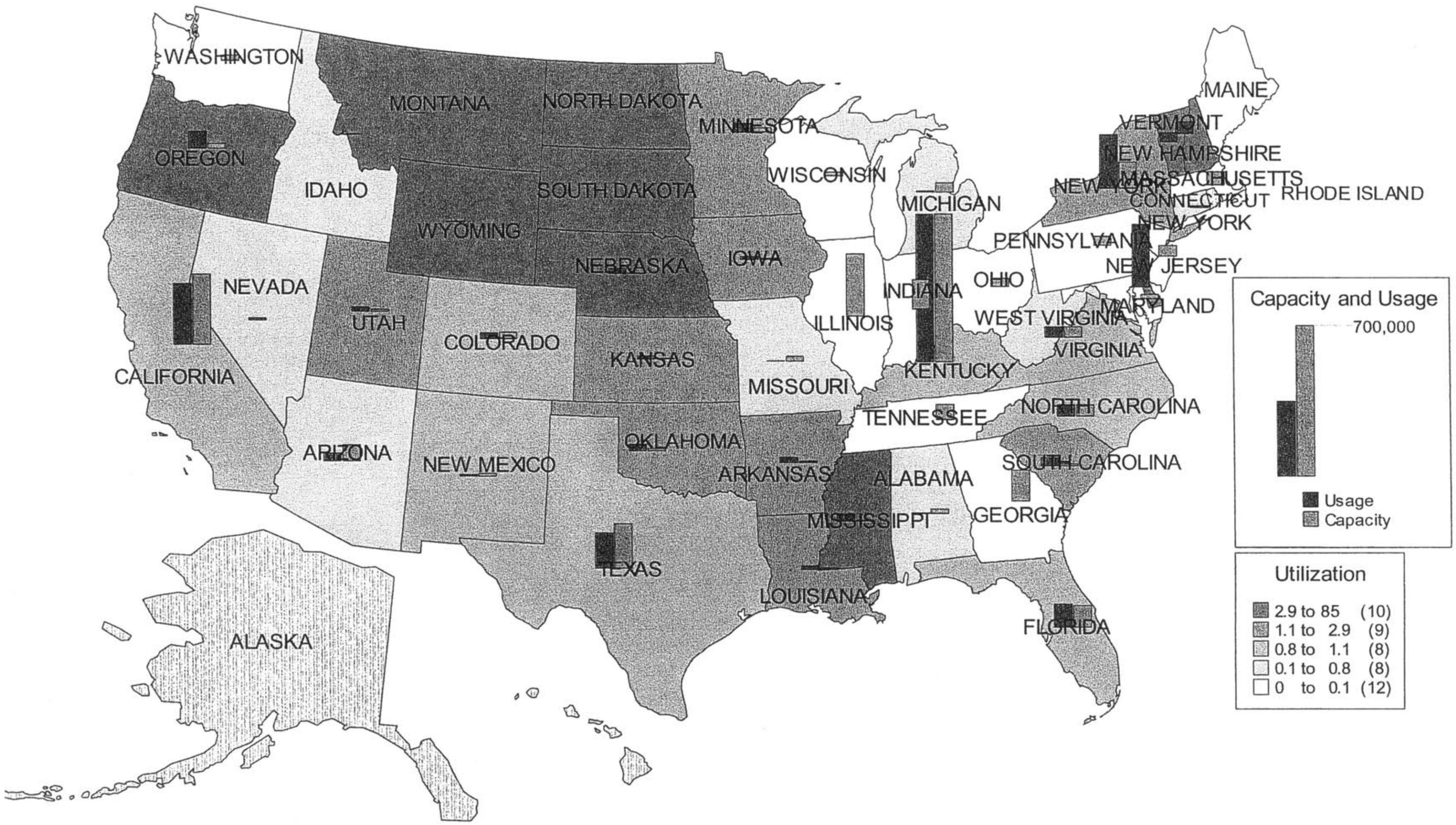
Appendix D3. Unconstrained Plan at 40% Volume.



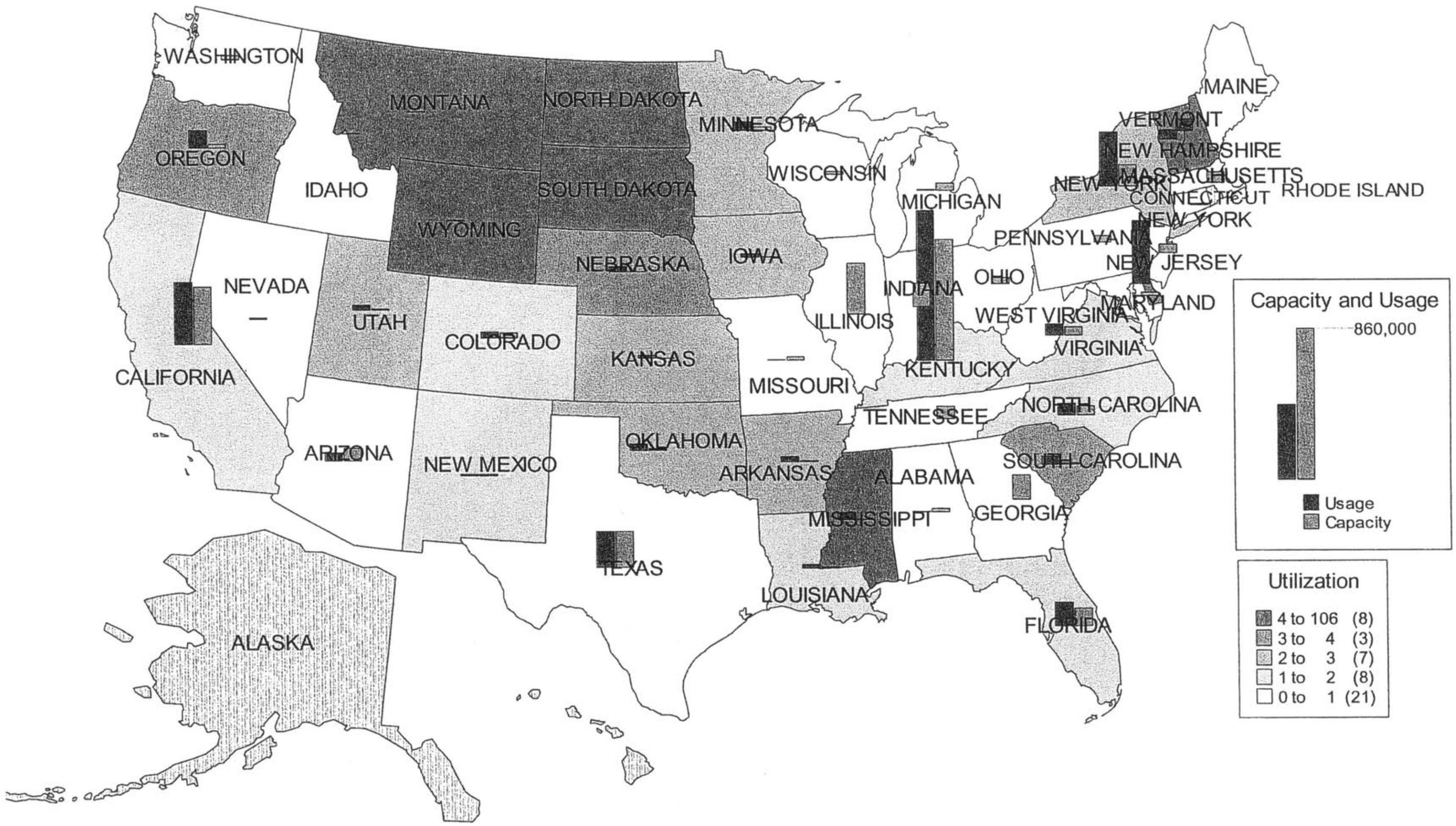
Appendix D4. Unconstrained Plan at 60% Volume.



Appendix D5. Unconstrained Plan at 80% Volume.



Appendix D6. Unconstrained Plan at 100% Volume.



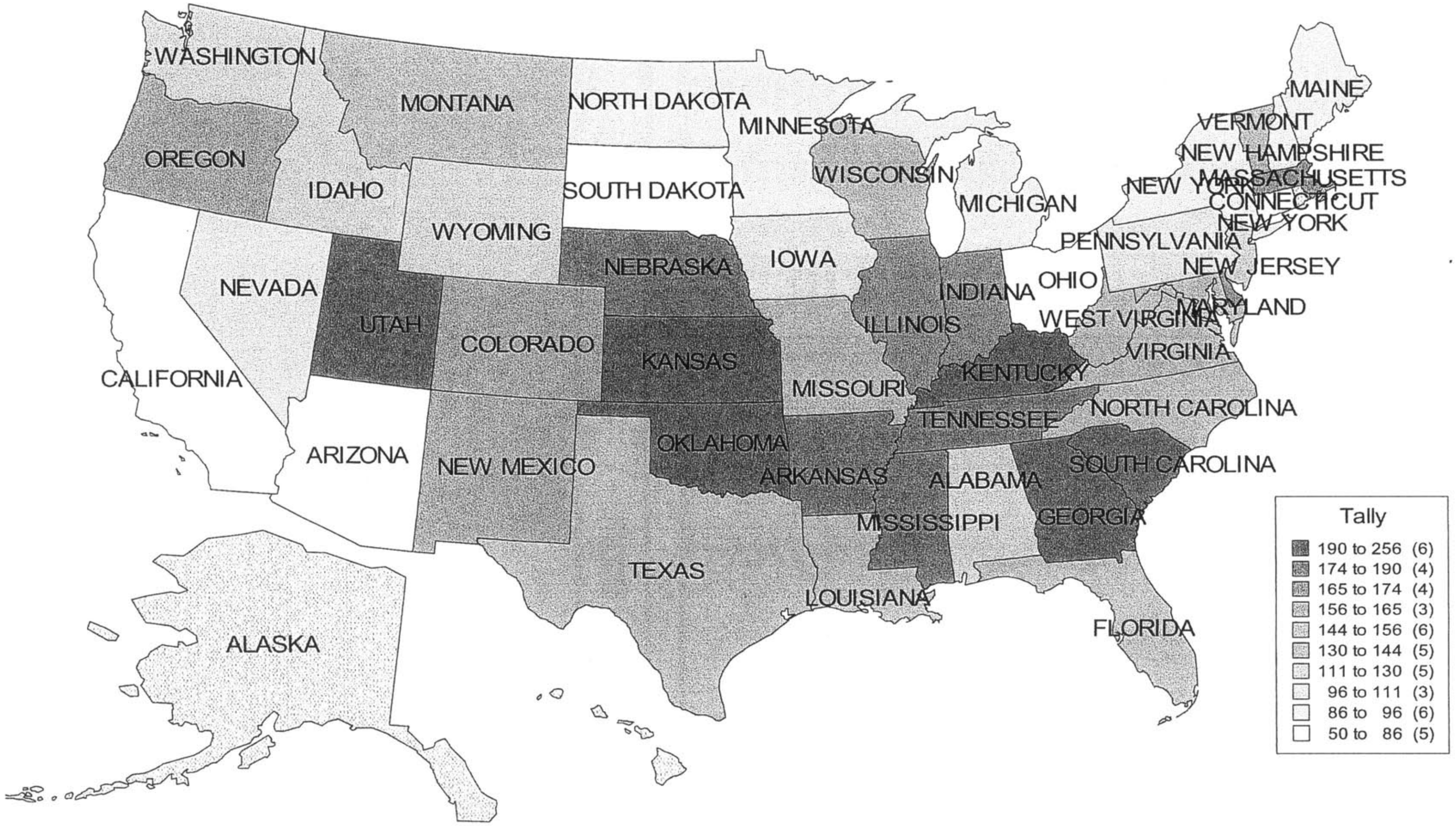
Appendix E1. Single SKU Network Optimization Objective Function

Index	Failure Rate	Part Cost	Part Weight (lbs)	25% Volume Objective	50% Volume Objective	50% Volume Objective	100% Volume Objective	25->50 %increase	50->75 %increase	75->100 %increase
1	0.0001	10	1	1,958,270	5,294,640	10,088,300	16,684,300	170.4%	90.5%	65.4%
2	0.0001	10	10	2,135,600	5,667,720	10,657,400	17,463,700	165.4%	88.0%	63.9%
3	0.0001	10	50	3,738,650	9,126,420	16,184,400	24,871,500	144.1%	77.3%	53.7%
4	0.0001	10	150	4,689,770	11,224,700	19,274,600	29,238,900	139.3%	71.7%	51.7%
5	0.0001	100	1	2,633,270	6,643,780	12,113,300	19,386,500	152.3%	82.3%	60.0%
6	0.0001	100	10	2,810,600	7,021,300	12,652,000	20,152,500	149.8%	80.2%	59.3%
7	0.0001	100	50	4,413,650	10,460,900	18,234,700	27,571,600	137.0%	74.3%	51.2%
8	0.0001	100	150	5,374,310	12,506,800	21,377,900	31,924,200	132.7%	70.9%	49.3%
9	0.0001	500	1	5,633,270	12,643,800	21,113,300	31,386,500	124.4%	67.0%	48.7%
10	0.0001	500	10	5,810,600	13,017,700	21,679,100	32,144,600	124.0%	66.5%	48.3%
11	0.0001	500	50	7,413,650	16,508,800	27,235,000	39,567,000	122.7%	65.0%	45.3%
12	0.0001	500	150	8,376,400	18,514,300	30,432,700	43,901,300	121.0%	64.4%	44.3%
13	0.0001	1000	1	9,383,270	20,143,800	32,363,300	46,386,500	114.7%	60.7%	43.3%
14	0.0001	1000	10	9,560,600	20,522,400	32,928,900	47,144,600	114.7%	60.5%	43.2%
15	0.0001	1000	50	11,163,700	23,943,400	38,444,100	54,573,400	114.5%	60.6%	42.0%
16	0.0001	1000	150	12,114,800	26,058,900	41,716,000	58,923,600	115.1%	60.1%	41.2%
17	0.001	10	1	2,315,410	6,061,260	11,264,200	18,309,600	161.8%	85.8%	62.5%
18	0.001	10	10	2,829,210	7,129,080	12,908,400	20,598,000	152.0%	81.1%	59.6%
19	0.001	10	50	7,447,550	17,194,100	28,262,000	42,312,800	130.9%	64.4%	49.7%
20	0.001	10	150	10,154,300	23,135,800	36,597,800	55,238,400	127.8%	58.2%	50.9%
21	0.001	100	1	2,990,770	7,411,740	13,299,200	21,007,300	147.8%	79.4%	58.0%
22	0.001	100	10	3,504,570	8,487,350	14,987,200	23,271,300	142.2%	76.6%	55.3%
23	0.001	100	50	8,122,910	18,526,300	30,351,500	45,038,100	128.1%	63.8%	48.4%
24	0.001	100	150	10,830,800	24,406,700	38,981,500	57,401,500	125.3%	59.7%	47.3%
25	0.001	500	1	5,992,370	13,412,400	22,299,200	33,004,800	123.8%	66.3%	48.0%
26	0.001	500	10	6,506,170	14,478,200	23,939,400	35,313,600	122.5%	65.3%	47.5%
27	0.001	500	50	11,124,500	24,524,200	39,431,000	56,966,700	120.5%	60.8%	44.5%
28	0.001	500	150	13,867,600	30,465,600	48,215,900	69,767,600	119.7%	58.3%	44.7%
29	0.001	1000	1	9,744,370	20,910,600	33,584,300	47,986,500	114.6%	60.6%	42.9%
30	0.001	1000	10	10,258,200	21,984,800	35,260,700	50,284,200	114.3%	60.4%	42.6%
31	0.001	1000	50	14,876,500	32,079,500	51,029,400	71,008,200	115.6%	59.1%	39.2%
32	0.001	1000	150	17,619,600	37,795,500	59,879,900	84,849,500	114.5%	58.4%	41.7%
33	0.01	10	1	2,874,280	7,216,300	13,094,600	20,382,700	151.1%	81.5%	55.7%
34	0.01	10	10	3,899,480	9,340,970	16,124,200	24,025,300	139.5%	72.6%	49.0%
35	0.01	10	50	13,163,400	27,580,600	42,194,700	60,497,800	109.5%	53.0%	43.4%
36	0.01	10	150	18,112,100	37,559,400	55,453,800	80,854,300	107.4%	47.6%	45.8%
37	0.01	100	1	3,551,530	8,579,550	15,217,000	23,172,200	141.6%	77.4%	52.3%
38	0.01	100	10	4,560,770	10,616,900	18,204,500	26,615,000	132.8%	71.5%	46.2%
39	0.01	100	50	13,758,400	28,973,500	44,308,700	64,510,000	110.6%	52.9%	45.6%
40	0.01	100	150	19,297,100	38,919,900	57,945,000	83,998,700	101.7%	48.9%	45.0%
41	0.01	500	1	6,561,530	14,547,400	24,232,100	35,209,800	121.7%	66.6%	45.3%
42	0.01	500	10	7,573,070	16,713,800	27,202,000	38,435,800	120.7%	62.8%	41.3%
43	0.01	500	50	16,695,600	36,056,700	53,779,300	76,297,700	116.0%	49.2%	41.9%
44	0.01	500	150	22,642,400	45,366,200	67,082,900	97,194,700	100.4%	47.9%	44.9%
45	0.01	1000	1	10,324,000	22,105,300	35,482,200	50,284,600	114.1%	60.5%	41.7%
46	0.01	1000	10	11,335,600	24,137,000	38,715,700	53,829,400	112.9%	60.4%	39.0%
47	0.01	1000	50	20,538,900	43,750,800	64,385,400	91,356,100	113.0%	47.2%	41.9%
48	0.01	1000	150	25,893,500	52,864,100	78,224,300	111,832,000	104.2%	48.0%	43.0%
49	0.1	10	1	3,382,250	8,295,290	14,839,200	22,001,400	145.3%	78.9%	48.3%
50	0.1	10	10	4,865,910	11,102,900	18,478,100	26,137,600	128.2%	66.4%	41.5%
51	0.1	10	50	18,104,200	35,831,100	54,287,900	72,592,900	97.9%	51.5%	33.7%
52	0.1	10	150	25,418,400	48,808,700	73,641,700	98,598,600	92.0%	50.9%	33.9%
53	0.1	100	1	4,074,170	9,657,920	16,934,300	24,736,200	137.1%	75.3%	46.1%
54	0.1	100	10	5,545,000	12,594,600	20,609,100	28,874,400	127.1%	63.6%	40.1%
55	0.1	100	50	18,764,600	37,296,800	56,477,200	75,305,900	98.8%	51.4%	33.3%
56	0.1	100	150	26,192,700	50,404,400	75,920,600	101,458,000	92.4%	50.6%	33.6%
57	0.1	500	1	7,149,370	15,708,900	26,158,900	36,771,300	119.7%	66.5%	40.6%
58	0.1	500	10	8,633,030	18,509,500	29,846,400	40,942,000	114.4%	61.2%	37.2%
59	0.1	500	50	21,935,600	43,629,500	65,813,000	90,167,500	98.9%	50.8%	37.0%
60	0.1	500	150	29,279,900	56,594,000	84,987,400	113,818,000	93.3%	50.2%	33.9%
61	0.1	1000	1	10,993,400	23,280,600	37,738,400	51,708,700	111.8%	62.1%	37.0%
62	0.1	1000	10	12,464,200	26,046,300	41,698,400	56,095,600	109.0%	60.1%	34.5%
63	0.1	1000	50	25,955,100	50,922,700	77,415,500	102,469,000	96.2%	52.0%	32.4%
64	0.1	1000	150	33,156,100	64,150,800	97,085,500	128,853,000	93.5%	51.3%	32.7%

Appendix E2. Single SKU Network Optimization Run Times

Index	Failure Rate	Part Cost	Part Weight (lbs)	25% Volume Time	50% Volume Time	50% Volume Time	100% Volume Time
1	0.0001	10	1	1020	565	5268	305
2	0.0001	10	10	1232	1232	1591	268
3	0.0001	10	50	688	430	328	395
4	0.0001	10	150	233	298	718	124
5	0.0001	100	1	1113	625	5231	352
6	0.0001	100	10	1320	1265	2844	223
7	0.0001	100	50	369	646	204	375
8	0.0001	100	150	98	325	556	296
9	0.0001	500	1	1102	571	5094	352
10	0.0001	500	10	1230	1071	3549	438
11	0.0001	500	50	431	349	210	534
12	0.0001	500	150	161	337	215	262
13	0.0001	1000	1	1147	698	5331	355
14	0.0001	1000	10	1299	219	1246	429
15	0.0001	1000	50	491	829	253	258
16	0.0001	1000	150	301	365	227	294
17	0.001	10	1	1569	3719	3188	427
18	0.001	10	10	1476	4044	1311	900
19	0.001	10	50	2403	2060	773	72
20	0.001	10	150	3139	1137	1007	48
21	0.001	100	1	1665	3510	2820	530
22	0.001	100	10	1076	0	2631	548
23	0.001	100	50	1420	1426	1122	88
24	0.001	100	150	5078	1829	867	60
25	0.001	500	1	1700	4459	2876	549
26	0.001	500	10	1531	3338	2620	369
27	0.001	500	50	1334	2924	956	309
28	0.001	500	150	1605	3616	1406	121
29	0.001	1000	1	1696	3473	3229	607
30	0.001	1000	10	1436	4718	1415	329
31	0.001	1000	50	1205	2795	1411	691
32	0.001	1000	150	3125	4925	979	249
33	0.01	10	1	669	1896	795	225
34	0.01	10	10	735	920	459	241
35	0.01	10	50	0	2254	1696	313
36	0.01	10	150	35455	559	1132	308
37	0.01	100	1	745	2044	759	247
38	0.01	100	10	615	849	533	353
39	0.01	100	50	0	3267	2318	253
40	0.01	100	150	0	1058	845	343
41	0.01	500	1	752	1948	1761	158
42	0.01	500	10	690	1382	1787	355
43	0.01	500	50	3010	0	4088	245
44	0.01	500	150	0	2536	2078	308
45	0.01	1000	1	734	1887	1306	235
46	0.01	1000	10	653	795	521	324
47	0.01	1000	50	6439	5311	5436	293
48	0.01	1000	150	5966	6253	2218	368
49	0.1	10	1	220	1910	900	330
50	0.1	10	10	281	2845	415	458
51	0.1	10	50	0	1993	1693	602
52	0.1	10	150	1596	3269	3021	656
53	0.1	100	1	237	2262	2411	336
54	0.1	100	10	249	267	490	507
55	0.1	100	50	0	785	1318	685
56	0.1	100	150	1331	910	1721	661
57	0.1	500	1	240	1826	1753	393
58	0.1	500	10	279	1033	866	429
59	0.1	500	50	0	1403	1102	217
60	0.1	500	150	2648	3106	4175	604
61	0.1	1000	1	253	2393	1248	596
62	0.1	1000	10	248	263	1372	426
63	0.1	1000	50	0	2770	1250	650
64	0.1	1000	150	4735	1541	1719	585

Appendix E3. State Tally of Single SKU Network Optimization Scenarios

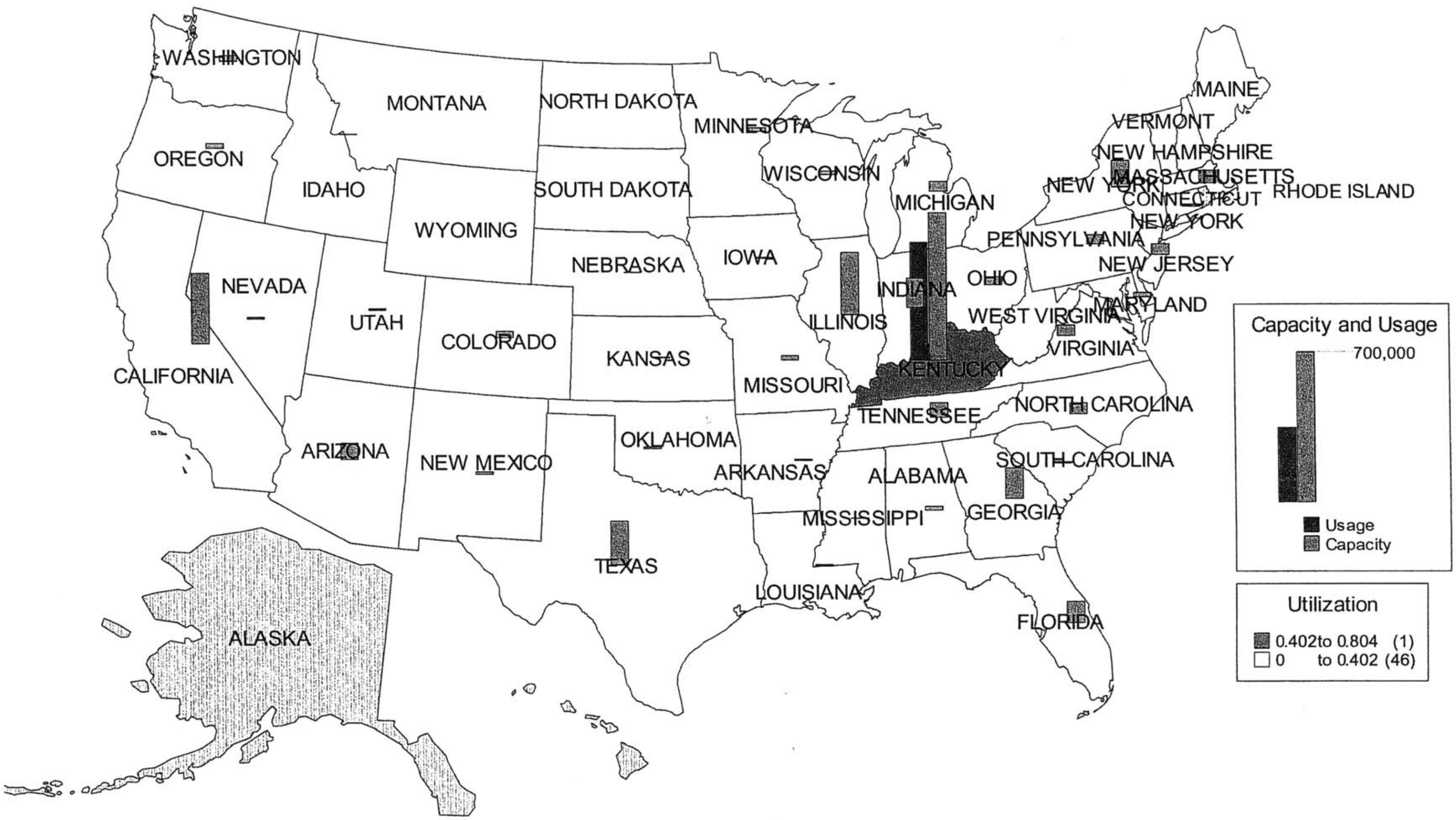


Appendix F1. Network Optimization Summary

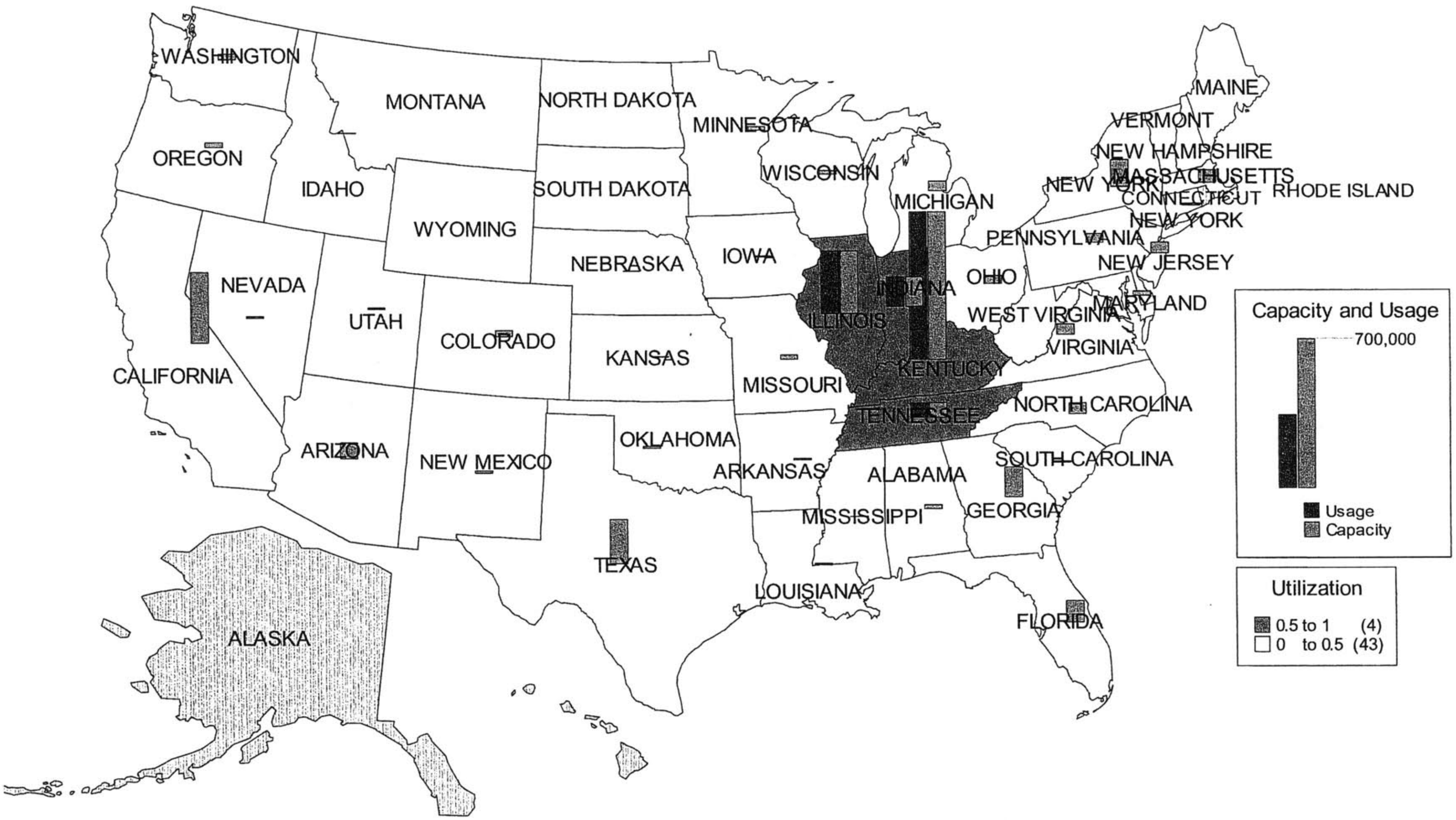
			20% Volume		40% Volume		60% Volume		80% Volume	
State Code	**State Name**	**Capacity**	**Usage**	**Utilization**	**Usage**	**Utilization**	**Usage**	**Utilization**	**Usage**	**Utilization**
AL	Alabama	26130	0	0%	0	0%	0	0%	26130	100%
AR	Arkansas	14750	0	0%	0	0%	0	0%	14750	100%
AZ	Arizona	82472	0	0%	0	0%	0	0%	0	0%
CA	California	333756	0	0%	0	0%	0	0%	0	0%
CO	Colorado	37420	0	0%	0	0%	37420	100%	37420	100%
CT	Connecticut	16408	0	0%	0	0%	0	0%	0	0%
DE	Delaware	3700	0	0%	0	0%	0	0%	3700	100%
FL	Florida	106434	0	0%	0	0%	0	0%	106434	100%
GA	Georgia	146814	0	0%	0	0%	146814	100%	146814	100%
IA	Iowa	11400	0	0%	0	0%	0	0%	11400	100%
ID	Idaho	11704	0	0%	0	0%	0	0%	11704	100%
IL	Illinois	297029	0	0%	297029	100%	297029	100%	297029	100%
IN	Indiana	141934	0	0%	141934	100%	141934	100%	141934	100%
KS	Kansas	9800	0	0%	0	0%	9800	100%	9800	100%
KY	Kentucky	692135	555900	80%	692135	100%	692135	100%	692135	100%
LA	Louisiana	13976	0	0%	0	0%	0	0%	13976	100%
MA	Massachusetts	67761	0	0%	0	0%	67761	100%	67761	100%
MD	Maryland	27271	0	0%	0	0%	0	0%	27271	100%
ME	Maine	3045	0	0%	0	0%	3045	100%	0	0%
MI	Michigan	49730	0	0%	0	0%	0	0%	49730	100%
MN	Minnesota	25601	0	0%	0	0%	0	0%	25601	100%
MO	Missouri	27974	0	0%	0	0%	27974	100%	27974	100%
MS	Mississippi	10000	0	0%	0	0%	10000	100%	10000	100%
MT	Montana	1360	0	0%	0	0%	0	0%	0	0%
NC	N Carolina	58066	0	0%	0	0%	0	0%	58066	100%
ND	N Dakota	1443	0	0%	0	0%	0	0%	0	0%
NE	Nebraska	10000	0	0%	0	0%	10000	100%	10000	100%
NH	New Hampshire	697	0	0%	0	0%	0	0%	0	0%
NJ	New Jersey	55769	0	0%	0	0%	0	0%	55769	100%
NM	New Mexico	17891	0	0%	0	0%	0	0%	17891	100%
NV	Nevada	16000	0	0%	0	0%	0	0%	16000	100%
NY	New York	128915	0	0%	0	0%	0	0%	0	0%
OH	Ohio	44673	0	0%	0	0%	0	0%	0	0%
OK	Oklahoma	15900	0	0%	0	0%	15900	100%	15900	100%
OR	Oregon	28341	0	0%	0	0%	0	0%	28341	100%
PA	Pennsylvania	47651	0	0%	0	0%	0	0%	47651	100%
SC	S Carolina	15170	0	0%	0	0%	15170	100%	15170	100%
SD	S Dakota	751	0	0%	0	0%	0	0%	0	0%
TN	Tennessee	76100	0	0%	72002	95%	76100	100%	76100	100%
TX	Texas	213205	0	0%	0	0%	212916	100%	213205	100%
UT	Utah	15020	0	0%	0	0%	15020	100%	15020	100%
VA	Virginia	56847	0	0%	0	0%	0	0%	56847	100%
VT	Vermont	4800	0	0%	0	0%	0	0%	4800	100%
WA	Washington	32891	0	0%	0	0%	0	0%	32891	100%
WI	Wisconsin	24916	0	0%	0	0%	0	0%	24916	100%
WV	West Virginia	3750	0	0%	0	0%	3750	100%	3750	100%
WY	Wyoming	217	0	0%	0	0%	217	100%	0	0%

	20% Volume	40% Volume	60% Volume	80% Volume
Solution Run Time (seconds)	335	2727	27385	86410
Total Cost	$ 2,709,400	$ 7,423,790	$ 11,409,400	$ 17,074,300
Best Bound	$ 2,709,400	$ 7,418,130	$ 11,409,400	$ 17,074,300
Optimality Gap	0.00%	0.08%	0.00%	0.00%

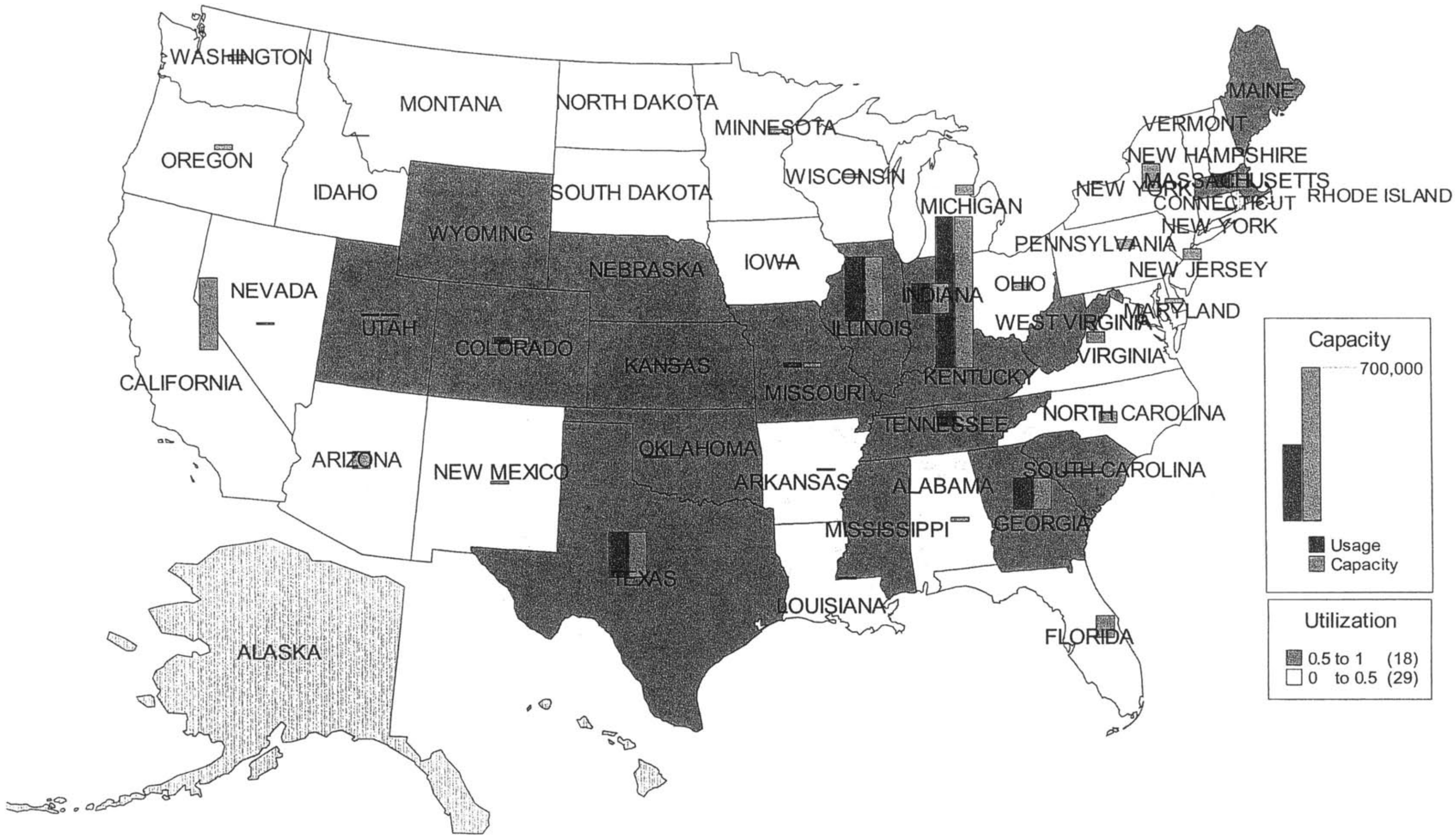
Appendix F2. Network Optimization at 20% Volume.



Appendix F3. Network Optimization at 40% Volume.



Appendix F4. Network Optimization at 60% Volume.



Appendix F5. Network Optimization at 80% Volume.